Design tools for port and grid infrastructure planning for floating wind and wave industries

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ABSTRACT

This thesis considers the development of one floating wave and one floating wind energy technology for their application in the Western Europe marine Exclusive Economic Zone (EEZ) and the associated port and grid connection infrastructure required to support growth in deployment. In this thesis, the Western European EEZ incorporates the marine zones of Portugal, Spain, France, Ireland, The United Kingdom, Norway, Denmark, Germany, The Netherlands and Germany. The process associated with developing infrastructure can be lengthy and complex, therefore this work presents a series of methods and evidence to expedite assessments. The core areas assessed for the development of floating wave and wind energy at array scale are evaluated as mooring suitability, power production, marine planning sensitivity and port/grid infrastructure capabilities.

Three modelling processes were developed across four time frames of 2018, 2020, 2025 and 2030 to identify the following, 1) basic site potential, 2) costed site potential and 3) infrastructure assessment. The first model constrained the marine zones according to assessment criteria and identified that by 2030, an approximate 300,000km^2 of floating wave or 260,000km^2 floating wind across the marine zones of Western Europe. This could equate to approximately 15TW and 4.2TW of installable capacity. The second modelling approach sought to allocate sites to theoretically suitable infrastructure based on location and fixed hosting values for port and grid capacity outlining a cost of energy. It was found that a total of 38GW and 75GW of respective wave and wind capacity could be considered capable of being cost feasible, defined as less than 100£/MWh, by 2030. The third modelling approach examined the more practical nature of the two infrastructure types. A grid assessment model utilised a genetic algorithm solver to evaluate a market mix assessing the energy penetration in Western Europe. A port operations model assessed the feasible build out time. It was found that after power market and port modelling, only 3.9GW and 13.6GW of wave and wind was practically deployable. Energy market modelling highlighted that 90% of wave and 80% of wind capacity was reduced due to the lack of access to suitable volumes of demand as well as a clash between production variability due to seasonal and diurnal demand profiles.

Furthermore, it was found that by 2030 the electrical grid infrastructure was twice as likely to reduce capacity potential, although impacts were location specific. This thesis also highlighted how groups of countries working in an energy partnership could connect greater numbers of potential sites within the combined EEZ. The best performer being a power union of Denmark and Norway, with vast numbers of sites in Norway being connected to the Danish electrical grid

system. This highlights that policy makers could utilise this type of understanding to evaluate infrastructure but also expand the use of decision tools in infrastructure planning.

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DECLARATION

I declare that this thesis was composed by myself, that the thesis contained herein is my own except where explicitly stated otherwise in the text, and that this thesis has not been submitted for any other degree or professional qualification except as specified.

Signed:

Thomas Francis van Lanschot

Date: 02/12/2020

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NOMENCLATURE

Abbreviations

AEP	*Annual Energy Production*
AHP	*Analytical Hierarchy Process*
BE	*Belgium*
CAPEX	*Capital Expenditure*
CTV	*Crew Transfer Vehicles*
DE	*Germany*
DISP	*Dispatchable Fossil Generation*
DK	*Denmark*
EEZ	*Exclusive Economic Zone*
EIA	*Environmental Impact Assessment*
ENTSOE	*European Network Transmission Operator Electricity Group*
EMODnet	*European Marine Observation and Data Network*
ES	*Spain*
EU	*European Union*
FR	*France*
GA	*Genetic Algorithm*
GIS	*Geographical Information System*
GMD	*Geometric Mean Distance*
GMR	*Geometric Mean Radius*
GSW	*Grid Suitability Weighting*
GVA	*Gross Value Added*
HVAC	*High Voltage Alternating Current*
HVDC	*High Voltage Direct Current*
IDW	*Inverse Distance Weighing*
JONSWAP	*Joint North Sea Wave Project*
LCOE	*Levellised Cost of Energy*
MCDM	*Multi Criteria Decision Making*
MEP	*Mean Energy Production*
MSP	*Marine Spatial Planning*
NHC	*Node Hosting Capacity*
NL	*Netherlands*
NO	*Norway*
NSO	*Network System Operators*
NSOG	*North Sea offshore grid*
NUTS	*Nomenclature of Territorial Units for Statistics*
OM	*Operations and Maintenance*

OPEX	*Operational Costs*
OSM	*Open Street Map*
PT	*Portugal*
REN	*Renewable Generation*
RTC	*Regional Transfer Capacity*
SI	*Suitability Index*
TSO	*Transmission System Operator*
TYDP	*Ten Year Development Plan*
UK	*United Kingdom*
VBA	*Visual Basic Applications*
WLC	*Weighted Linear Combination*
WPI	*World Port Index*
WWE	*Wave and Wind Energy*

Symbols

C_g	*Cost of Generation*	-
C	*Capacitance*	μF
D	*Diameter*	m
d	*Draught*	m
$C0_2$	*Carbon Dioxide*	-
f	*Frequency*	s^{-1}
f_m	*Mean Sea frequency*	s^{-1}
g	*Gravitational Force*	m/s^2
G_c	*Grid Connection*	-
Gi	*The Getis-Ord Statistic*	-
h	*Depth*	m
H_{hub}	*Hub Height*	m
H_{m0}	*Significant Wave Height*	m
I	*Individuals*	-
I_c	*Installation Cost*	£
L	*Line Distance*	m
Lc	*Inductance*	Ω/km
M_c	*Mooring Cost*	£
m_n	*Spectral Moment of order n*	$m^2\ (Hz)^n$
OM_c	*Operations & Maintenance Cost*	£
P	*Probability*	-
p	*Density of water*	kg/m^3
r	*Radius*	m
R	*Relative Cost*	£
SIL	*Surge Impedance Loading*	MW
T	*Wave Period*	s
T_e	*Wave Energy Period*	s
T_p	*Wave Peak Period*	s

U_{hub}	*Wind Speed At The Hub*	*m/s*
U_{record}	*Measurement Wind Speed*	*m/s*
wij	*Spatial Weight Between Cells*	-
ws	*Wind Speed*	*m/s*
Xj	*Attribute Value*	-
Z	*Statistical Significance*	-
Z0	*Surge Impedance*	*Ω*
Z_0	*Factor Of Roughness*	*m*
λ	*Mean Wavelength*	*m*
η	*Efficiency*	-
π	*Pi*	-
Σ	*Sum*	-
ε0	*Constant, permittivity of free space*	*F/m*

Values

kW	*Kilowatt*
MW	*Megawatt*
GW	*Gigawatt*
TW	*Terawatt*
kWh	*Kilowatt-hour*
MWh	*Megawatt-hour*
GWh	*Gigawatt-hour*
TWh	*Terawatt-hour*
m	*meter*
km	*Kilometre*
kV	*Kilovolt*
hrs	*Hours*
yrs	*Years*

ASSOCIATED PUBLICATIONS

van Lanschot, T., de Andres, A,. Forehand, D., Jeffrey, H. (2017). *Utilising GIS To Assess Impacts On The Siting Of Wind And Wave Energy And Its Associated Infrastructure*. Conference proceeding (EWTEC – European Wave and Tidal Energy Conference, Cork).

van Lanschot, T., Forehand, D., Jeffrey, H., (2018). *Development Of An Iterative Spatial Assessment For Regional Grid Connection For Floating Wave And Wind Energy Arrays.* Conference proceeding (ICOE – International Conference on Ocean Energy, Cherbourg).

PREFACE

“We live at a time when emotions and feelings count more than truth, and there is a vast ignorance of science.”

- Dr. James Lovelock –

The quote from Dr Lovelock was referenced by the late Sir David J. C. MacKay, chief scientific advisor to the United Kingdom (UK) Department of Energy and Climate Change [1]. It was Sir Mackay who advocated for frank discussions over the future of clean energy. To put aside emotional arguments and rhetoric for both renewable sceptics and enthusiasts to find a practical solution to a growing challenge.

1. INTRODUCTION

1.1 Electricity Consumption and Generation

Since the middle of the 20th century, the consumption of electricity in Europe has been on the rise. With a fivefold increase in consumption recorded since 1950, supplying this demand has become an ever-growing and evolving challenge, with Europe seeing an increase in net electricity generation of almost 1000 terawatt hour[1] (TWh) since 1990 levels from 2200TWh to 3100TWh in 2017 [2] and European consumption is expected to increase by a further 20% by 2050 [3]. In order to strive towards a cleaner and more sustainable future, a reduction in carbon-based energy generation has become a core goal, with a growth in renewable generation as a result. The ultimate goal of decarbonising the power sector is based on the practical reasoning that we cannot build vast amounts of fossil fuel power plants without toxifying our surroundings. The issue of how to meet demand with renewable power has always remained a challenge and Figure 1 illustrates the historic growth of renewable generation as a share of total generation in the European Union (EU) between 2004 and 2018.

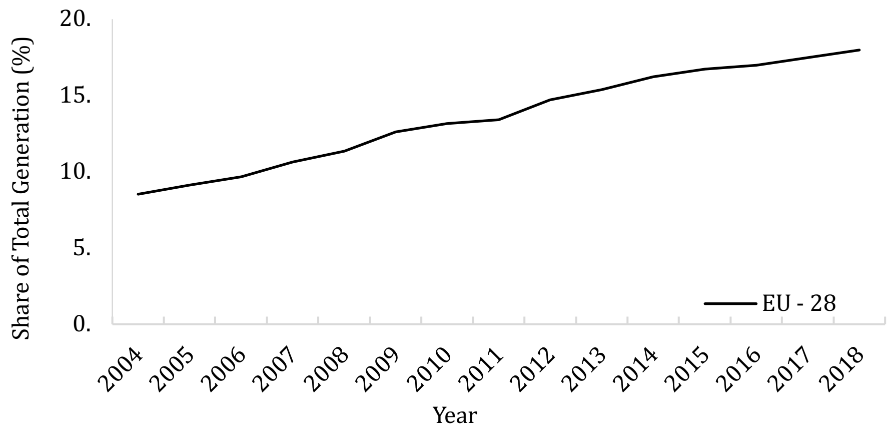
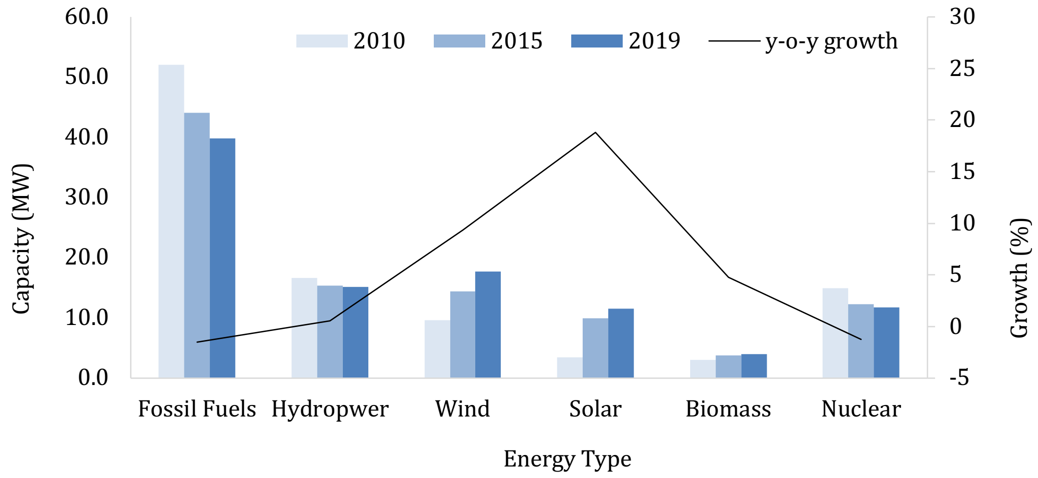


Figure 1. Renewable share of total European Union electricity generation from 2004, when the EU formalised the blocs energy policy [2].

[1] The standard unit of power measurement throughout this thesis are defined in terms of watts. Where a watt is the standard unit of power relating to the rate of energy transfer. Magnitude of power is pre-determined by the prefix of kilo (1000), mega (1000000), giga (10^9) and continues in numerical succession.

While it can be seen that renewable generation is increasing, with binding energy targets to achieve 32% renewable generation by 2030 and the general EU aim to be net zero by 2050, the issue of renewable growth is even more pertinent [4]. However, to achieve these goals the capacity additions of renewable sources must rapidly overtake fossil fuels within the coming decades. Figure 2 illustrates how generation was achieved between 2010 and 2018 and how capacity additions fluctuates across energy sources.



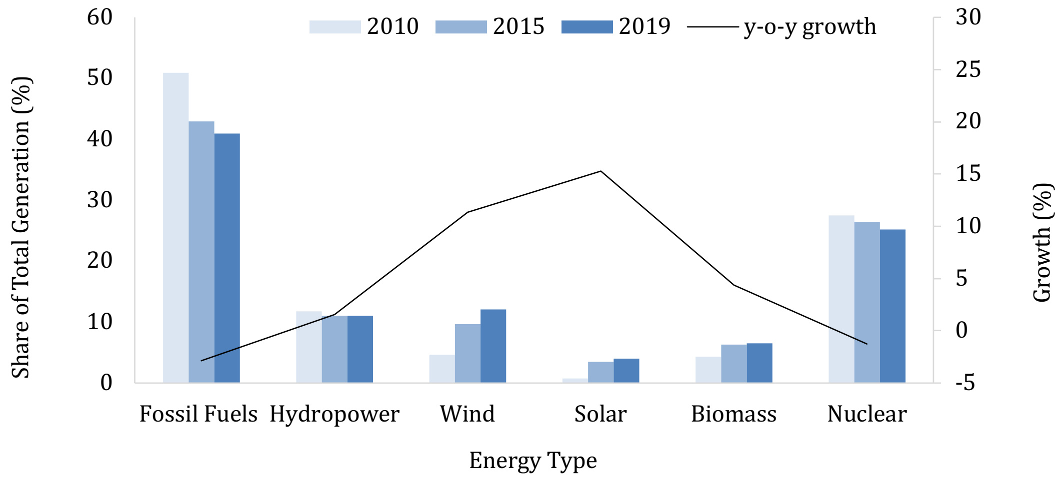


Figure 2. (Top) Installed capacity (Bottom) Generation as share of total including year-on-year (y-o-y) growth [2] [5]. While other forms of generation exist in the EU, e.g. geothermal, they represent a minimal portion, less than 1%, of the total energy supply and are not presented .

The dominance of fossil fuels is evident in Europe when considering these time frames. However, what can be discerned is the declining trend in fossil fuel installation with negative year on year (y-o-y) growth while an increase in each of the major renewables sources: wind, biomass and solar is observed.

Fossil Fuels: The tradition thermal generation of power utilising chiefly coal, oil and gas still make up the majority of power supply in the EU and in 2018 made up to 40% of total generation. However, coal generation reached its peak in the early 21st century and in most of Western Europe and has fallen into decline with most of Western Europe striving to phase out the coal sector entirely. In 2010 coal supplied over 25% of the EU's total power generation while in 2018 that had fallen too 20%. The second major fossil fuel is natural gas which in 2018 constituted 19% of total power generation, down from 23% in 2010. In northern Europe previously unattainable fields in the North Sea were exploited and in some countries like the UK gas fired power supplied over 40% of total power in 2018 [6]. However, for those countries not producing natural gas issues with the political challenge of over reliance on non-EU suppliers has seen considerable headwinds for gas fired power [7].

Nuclear Power: Seen in Figure 2, nuclear power is still a major source in the European energy mix at 25% in 2018 falling by only 2% from 2010. It has long supplied steady high volumes of power to many countries in Europe , most notably in France with approximately 70% generation capacity [8]. However, public concern, construction and operating cost, waste disposal issues and extensive decommissioning costs have seen in a withdrawal in public support. The costs of developing new nuclear power have come under serious scrutiny with Hinckley Point plant, projected to supply 7% of the UK's energy needs, is being quoted at over £20 billion. This would be at an electricity price of twice that of natural gas or onshore wind power of £93/MWh [9]. The nuclear legacy is further being questioned across Europe with Germany deciding to phase out all plants by 2036. This phase out will not only have an impact on Germany energy mixtures but the rest of Europe [10].

Hydropower: As can be seen in Figure 2, hydroelectricity in the EU is a major form of generation and approximately 11% share of total generation in 2018 with almost no change since 2010. It has long been favoured due to its clean and near instant generation capability. However, they are inherently limited to highly particular geographic locations to either, exploit river potential energy or store potential in vast reservoirs. The space needed for development in what are often considered naturally desirable areas has become contentious. While they remain a crucial part of the European energy mix the development of new hydro power has stalled in recent years, Figure 2.

Biomass: Biofuel driven plants that use biological processes to create energy for electrical conversion have become increasingly popular particularly in countries with high agricultural production. It too is on the rise with a doubling of capacity since 2010 with biomass supply 6.5% of total generation in 2018. However, due to the footprint of biological material required the viability of ever larger scales of generation is posing an issue [1].

Solar: The fastest growth renewables sector with and average y-o-y growth of 18% over the period 2010-2018, Solar has also been exploited in the last 10 years in growing numbers capturing approximately 4% of the generation share in 2018 up from 0.5 in 2010. However, this technology has a similar problem of maximising the energy extraction over the area required. To produce power at a gigawatt (GW) scale the footprint of solar farms would need to be considerably large. This coupled with expensive land prices in Europe have led to drawbacks in support with continued expansion and mass development of large utility scale in favour for smaller projects [1]. Furthermore, Solar power has conversion performance issues due to the variability of weather and solar irradiation which powers cells.

Wind: The largest renewable source of power generation in the EU in 2018 was wind capturing 14% of the total generation share, a near tripling of generation from 2010 levels at 4.5%. In 2018 capacity was the largest in the renewable sector with over 181GW installed [11]. This value is similar to that of natural gas as the second largest for of power generation type in Europe [11]. However, developments remain highly contentious due to, public opinion, land prices, reliability and variable performance. Similarly, to solar power, one of the most significant issues with wind energy generation is the intermittency in power supply caused by the variability in weather and corresponding wind speeds. This inability to call on wind power to satisfy demand leads to supply issues which hamper its adoption.

1.2 Moving Wind Offshore

As seen with other energy sources, the draw backs in poor power conversion performance and land use onshore have played a role in the drive for offshore wind. Western European countries that have long been exposed to harsh windswept environments have looked to harness this untapped form of energy. Like the offshore oil and gas industry, what was previously thought of as unfeasible is now widely being exploited. In the last 20 years, offshore wind has progressed to become a core part of the energy mix in Western Europe with over 22GW of installed capacity in 2019 up from 0.6MW in 2005 [5]. The sector is rapidly increasing with a y-o-y growth in installed capacity between 2015 and 2018 of 20% in 2016 and is currently the largest growing energy generation market in Europe [12], although onshore wind captures a larger share of total generation. Further, it is understood that the growth of offshore renewable power generation has led to resurgences in coastal economies as well as creating a new technology industry [13]. Public spending on national infrastructure that benefits local economies has seen a rise in support, as opposed to spending seen in nuclear power which is criticised for the economic stimulation of foreign countries [14]. The UK in 2019 captured 50% of the offshore wind capacity market share with approximately 10GW installed with plans to scale up with an additional 30GW over the coming decade.

The ability to construct and maintain offshore wind turbines in the last 3 decades has seen drastic cost reductions at ever greater water depth and distances from shore. Increasing turbine reliability and size have also led to a greater ability to deliver affordable clean energy [15]. The average offshore turbine in 2005 had a rated power of 3MW, devices in 2018 reached 8MW and development is taking place to produce 12MW and possible 20MW devices through the decade to 2030. Although developing in the open sea may have little public resistance to land use, the marine zone that has traditionally been developed is becoming more congested [16]. The lure of even greater resources and the ability to build larger farms is something that is now being considered. A countries Exclusive Economic Zone (EEZ) represents the sovereign marine area from which the country may conduct marine operations. The remaining further EEZ which may be exploited for development by a country is now being explored [16]. The industry is driving the trend and moving to ever more remote and challenging offshore locations in search of attractive resources with arrays being built in water deeper than 40m at over 100km from shore [17]. Further the size of arrays has also grown from tens of MW's to over hundreds of MW with ever larger being planned.

1.2.1 Floating Technologies

Two forms of offshore renewables have been highlighted for their ability to exploit more remote but potentially better resources, those being floating wind and floating wave energy technologies. Floating offshore wind has not seen the same development of fixed offshore wind due to the challenges of operating in what are often harsh climates. However, as understanding in the support system and engineering in fixed offshore wind has grown, and costs have fallen the development of large scale offshore floating wind concepts have become a practical reality. The lessons learned have been applied to a number of floating designs and are now being explored for commercialisation. Three main contenders, Figure 3, have been developed to what is being considered a commercial reality [18] and several commercial farms are being considered at 10's of MW capacity utilising these design types [19].

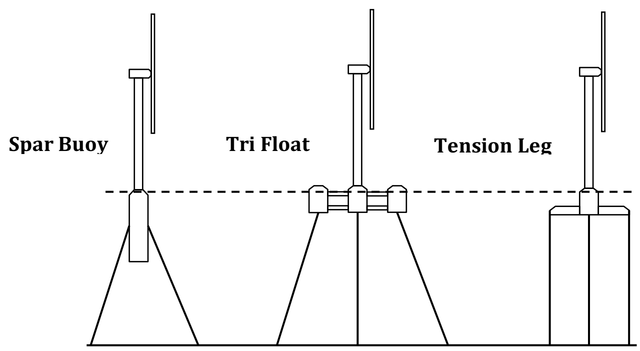


Figure 3. Three emerging floating wind technology types reaching commercialisation. Spar buoy: A substructure which gains its stability from having the centre of gravity lowered below the water line with a cylindrical ballast. Tri float: This type is a form of semi-submersible platform which

floats partially submerged while anchored to the seabed. Tension leg platform: This type utilises tension in its mooring system to reduce the amount of ballast needed in its shallow draft substructure [18].

In October 2017 a pilot array for a floating wind array was grid connected in Scotland in partnership with the oil and gas firm Equinor [20]. The array has borrowed much in its conception of this type of mooring technology from the oil and gas industry. It utilises the spar buoy design is moored at a depth of 100m and in 2009 a pilot device was successfully tested at full scale leading to the array pilot project. Known as the Hywind array it was able to achieve generation efficiency results far beyond fixed offshore wind farms. In winter months a fixed offshore wind farm typically achieves an efficiency of generation of 45-60% of its rated capacity in MW. In comparison, Hywind achieved averages of approximately 65% of its rate capacity over winter months [21].

Wave energy extraction has also long been in development, since early conception and serious technology developments taking place in the 80's [22]. This more nascent sector has seen several forms of devices that have been trialled with some small-scale deployment. Although with less technology convergence, the fundamental principle remains to extract the kinetic motional energy through a body floating in the water and to convert that to usable electrical energy. By exploiting one or more degree of motional freedom, floating converters differ from their nearshore bottom mounted relatives [23]. Figure 4 demonstrates three floating technology types that have reached full scale development or to some degree commercial pilot operation.

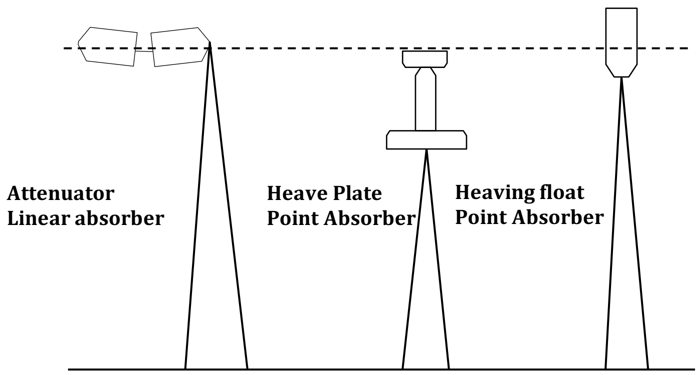


Figure 4. Floating wave energy point absorber technology types that have reached full scale development. Attenuator: The attenuator operates with a series of connected bodies parallel to the prevailing wave direction and rides the surface waves. Heave Plate: Absorbers that operate near the surface of water with a counterweight at the bottom of the structure. Heaving Float: In contrast to the plate absorbers this type uses no counterweight and relies on the surface movement of water to generate power.

Attenuator devices harness energy from the relative motion through the movement in coupling arms between the bodies. This form of devices reached full scale commercial pilot test farm status with the Pelamis wave energy converter in 2008, however, this has since 2014 closed [24]. Another floating offshore wave technology type that has reached a full-scale pilot stage are point absorbers. The technology absorbs energy from all directions through motion on or near the water surface and converts wave motion of the buoyant top relative to, in the cases in Figure 4, a base plate or tether into electrical power. Three such devices are: the fully submerged tether CETO device, part of a 3 device array [25], the OPT heave plate device, reaching full scale devices with plans for large arrays [26] and the Core Power Device with a series of devices ranging from kW to 0.5MW scale devices [27].

1.3 Why Floating Wave and Wind?

A commonly ratio used to determine power generation efficiency, the capacity factor, is the relationship of the total power output over a given time and the maximum rated capacity that could be achieved over time. Onshore wind farms have an average capacity factor of 25-30%, meaning it produced over a period of operation, commonly a year, 25-30% of the rated capacity [15]. Offshore wind in comparison has seen this value rise to 35-45% due to the resource being better with higher wind speeds, measured in meters per second (m/s), and decreasing variability in wind speed [28]. The drive to exploit the better offshore resource with limited development constraints is therefore an attractive proposition. Figure 5 demonstrates how greater wave power, typically measured as kW per meter and wind speed is often located away from land mass and in more remote regions.

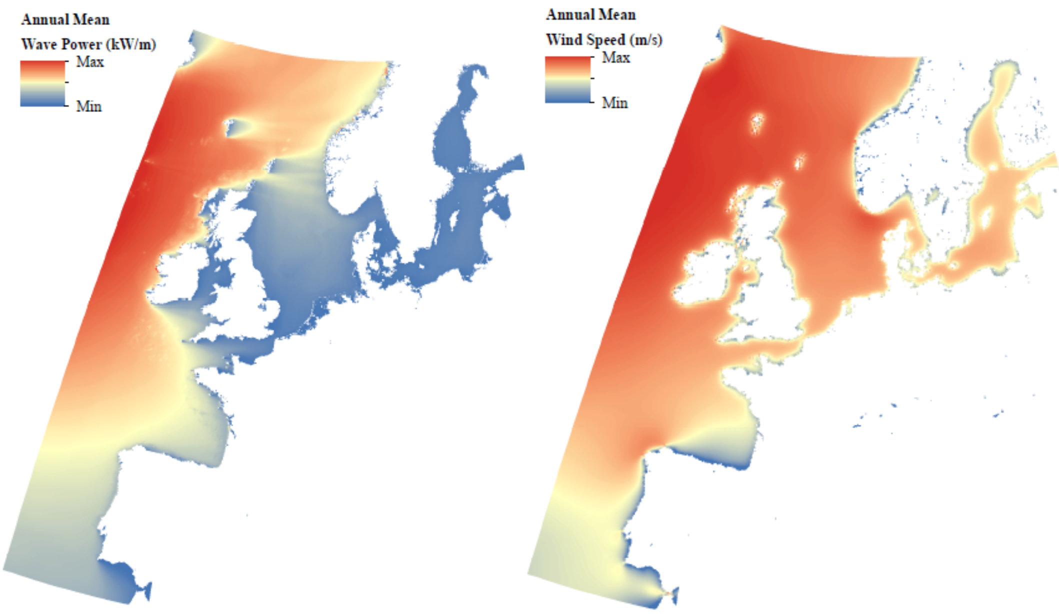


Figure 5. Example offshore wave (left) and wind (right) mean annual resource. Resource characterisation, established from data provided by the University of Athens [28]. High intensity resource regions are located in particular sites demonstrating the impact of location for floating

wave and wind technologies. For both technologies' resources of the West Atlantic coast are most favourable.

It is known that approximately 80% of the global offshore wind resource lies in water deeper than 60 m, which is the current fixed maximum depth [29] for a fixed bottom structure. This value is increasingly squeezed after considering the competition with other marine users closer to shore [16]. European wave energy resource potential estimates have the western Atlantic coastline at up to 75kW/m and 30-20kW/m for the North Sea [30]. Studies show that these regions have a potential wave power capacity of 290GW [31]. Although wave energy converters are still in the development stages with limited pilot success, understanding where this new form of electricity supply would be located is significant. Other forms of floating technologies have shown signs of significant success in their own field, not limited to, floating tidal and solar energies. However, in terms of technology maturity and commercialisation of floating offshore energies that could operate far from shore the potential energy floating wave and wind have remained the front runners to exploit these two types of offshore resource.

1.4 The Cost of Energy

The practical reason for not exploiting the resource sooner is one of engineering feasibility and cost. The cost of energy is commonly determined by the principle of payback return over a project lifetime and is commonly measured as price per megawatt hour (MWh). The principle, known as the Levellised Cost of Energy (LCOE) is one of the total capital and operational costs experienced by an energy system over its power production across its lifetime [23]. The report in the global investment trends in renewable energy found that the LCOE of solar, biomass, onshore wind had reached a fossil fuel competitive price. In many cases onshore wind and solar are being found to be cheaper than traditional fossil fuels at £50/MWh and £60/MWh [32]. The cost of offshore wind has also come down from approximately £100's/MWh to new projects being quoted at £50/MWh for the coming years and are expected to continue to fall [33]. As floating wave and wind are comparatively nascent technologies cost data is harder to establish. However, prices of £150/MWh and £300/MWh for wind and wave have been estimated in varying studies, [34] [35] [36] [37] [38] [39]. Current research and commercial reports have found that due to the ability for floating wind to harness lucrative resources, cost reduction will be seen. While variability will undoubtedly remain high, a consensus is that costs should continue to decline, with some estimated LCOE's quoted lower than onshore wind and gas by 2030. As technology performance improves and costs reduce, the lure of vast amounts of energy, could become a practical reality. Although far less developed when being compared to floating wind, wave energy still could show signs of potential as costs would too be expected to decline if developed at large array scale.

1.5 Associated Infrastructure

As with the fixed offshore wind industry, two forms of large-scale infrastructure are involved in facilitating floating renewable development, these include the port and grid capability. Ports provide the ability to build and maintain offshore structures and are, by the nature of operations, inherently crucial in their location relative to a site. In 2018 a joint floating wind industry report, between UK government and leading industrial partners identified the potential growth of the industry and the required infrastructure. It demonstrated that only a handful of ports out of 96 on the Atlantic coasts of Norway, United Kingdom and Spain could perform the necessary functions required [40]. This problem might be increased due to the congestion found in the key ports with other marine operators including those for the fixed offshore wind industry [41].

The capability for grid connection is also of great importance, as the power generated must reach the demand centres through an already complex system. As demand for clean energy is increasing there is a unilateral understanding that increasing load and new generation will require infrastructure change. For all forms of power this will require a development in transmission capabilities. In previous years as more wind power both on and offshore have come online several problems have arisen. This includes issues of: intermittency, increased energy prices, poor infrastructure and in cases the lack of infrastructure [42]. As seen in Figure 4 the more attractive wave and wind energy resources are often located on the fringes of the Western European coastline, grid capabilities in these more remote locations are weaker. In order for these prevalent issues to be addressed the capability of the grid to handle increased volumes without exacerbation is crucial.

Due to floating wave and wind energy (WWE) technologies being relatively new energy technologies in comparison with the fixed offshore wind industry, the associated regulation and infrastructure often lags behind what may be required. The time frame for infrastructure development can span decades [42]. Therefore, in order to make future energy decisions, targeted infrastructure development must take place in synergy with industry growth. As has been seen in the past port and grid infrastructure has constrained success. If energy targets are to be met through the development of floating energy systems, the requirements of the wave and wind industry must be addressed.

1.5.1 Research Hypothesis

It has become clear that Europe must generate increasing levels of clean cost-effective electricity to satisfy a growing demand for clean energy. However, current generation capabilities and associated infrastructure are insufficient to meet this growing problem.

To exploit the vast untapped high resource offshore resource the suitability locations of floating renewable power must first be assessed. To best support this exploitation, targeted policy and investment of suitable infrastructure must take place.

1.6 Literature Review

The research hypothesis posed by this thesis contain the key principles of site suitability, spatial planning, marine engineering, and transmission planning and infrastructure policy. These topics are continually being developed and researched in academia and industry. However, it is the combination of these core fields that are required to address the hypothesis.

1.6.1 Site Suitability & Spatial Analytics

Site suitability analysis for renewables has been explored through a number of studies using the application of spatial analytics. Spatial analysis involves using statistical databases with geographic properties to perform tasks. Studies to forecast the site potential of offshore renewables was seen in [43] [44] [45]. These assessments focus on the spatial relationships of multiple layers including the location of feasible development sites and the associated costs. A key method used in site selection is multi criteria decision analysis. The process works through multiple layers to form a combined linear analysis and identify statistical relationships. A weighted analysis is a common form of spatial statistical analysis in multi criteria problems. Combined variables are normalised to reach a combined value in a weighted linear combination (WLC). In site optimization the relative scoring of input criteria and subset variables requires a detailed understanding of the importance of challenges faced by the industry. This is not always possible and therefore most commonly multi criteria decision making (MCDM) analysis is applied with an analytical hierarchy process (AHP) model. The combination of these two statistical modelling approaches to renewable energy siting or marine spatial planning have been observed in [46], which addressed site selection of offshore wind and wave energy systems utilising GIS, [47] which considered a GIS multi-criteria evaluation for wind farm selection, [48] a site suitability analysis for offshore wind and [49] which sought to apply MCDM analysis to offshore wind potential energy yields. While robust in their statistical and spatial approaches to MCDM modelling they have consistent irregular weighting preferences and low consensus among common themes. Variations in types of weighted assessment for site suitability where reviewed in and [50].

1.6.2 AHP analysis

With spatial analytics being used with either an analytical hierarchy process (AHP), set theory, or industry established weightings. An industry or technical based weighting method was used in offshore wind farm site selection by the Scottish government in [51] and for marine energy devices in [52] by the US department of energy. The approach also seen in a floating industry report [53] for site selection as well as in [54] which considered multi-criteria site selection for offshore renewable energy platforms. These methods consist of multiple types of data in terms of spatial and attribute-based granularity. Further the type of data to be represented varies between discrete and continuous data. In order to represent the overlap potential of floating WWE with stakeholders a level of favourable variability must be applied to sites. In spatial analytics fuzzy logic is generally applied to account for these two types of condition [55]. Within this method variables are scaled either to a Boolean value of 0 or 1 and a standardised value between 0 – 1 according to defined parameters. This premise of fuzzy logic analysis pertains to the inaccuracies of values in a dataset and the level of representation. This particular method of fuzzy membership analysis for site suitability was also explored in [47] [56] [57] [58] [59]. Although these types of studies show the relationship between layers in an analytical sense there is an absence of infrastructure sensitivity. Most site assessments for offshore wind including these academic studies consider scenarios for ports and grid connection capabilities or simply consider the distance to any facility or coastline. However, such site assessments inherently are constrained and contain increased inaccuracies.

1.6.3 Marine Spatial Planning

Marine sites are inherently more complex as they become more congested and conflicts can arise. In order to assess the potential for new generation sites, and subsequent policy, Marine Spatial Planning (MSP) is often applied [16]. MSP can characterise importance and improve marine zonal management for stakeholders. Although, within the field of site selection for floating renewables, little direct progress has been made and across Europe there is an amount of variability with regards to MSP.

Some countries have defined policy and are moving to establish legislation such as, Ireland, France, Denmark, Belgium, the Netherlands and Portugal. Others, including Spain and the United Kingdom, have multiple regulatory bodies and frameworks for the management of marine resources. Within the EU, there have been several cohesive efforts, on national and international levels, to guide offshore renewable planning through framework aimed at MSP. Most notably and recently the EU's SEAENERGY 2020 project [60]. MSP has highlighted key concerns in marine user assessments, most notably, how to reduce conflict without reducing value. By enforcing segregation without understanding the sensitivities of stakeholders, economic value may become restricted. This was highlighted in an EU study on the effects of MSP on socio economics in forecasted trends. It showed a loss in value added to the economy was caused by growth of fixed wind industries if using strict segregation [61]. Furthermore, when considering the role of other marine stakeholders in MSP the relative sensitivities to the allocation of suitable marine space is increasingly more contentious. This was notable in 2015, where a UK offshore windfarm site was contested by the Netherlands due to infringement on bordering nature reserves. These issues, coupled with the ambitious energy policies of EU member states and ambitious low offshore costs, could create similar issues. Independent, site suitability, MSP and marine management schools of thought have been explored. A gap in the application and understanding of combining these methods has been identified. By assessing where the sector may be and how subsequent policy could impact sector growth in relation to marine planning these gaps could be addressed.

1.6.4 Stake Holder Value

The marine stakeholder 'value' could be for example, the environmental importance or financial importance to the country in question. Typically several stakeholders that could be impacted by this growth are identified as: aquaculture, marine tourism, coastal tourism, offshore industries, shipping, fishing, dredging/aggregate extraction and oil and gas [62]. Furthermore, the future offshore activities would need to avoid stakeholder structures, which could include pre-existing cables, pipelines and offshore fixed structures. Gross value added (GVA) is a common metric for determining industry importance. Studies into the relationship between, weighting, zonal management and industry have shown that these types of relationships can be used to highlight conflict [61]. The work, conducted by the EU Commission Directorate General of Maritime Affairs assessed that oil and gas, shipping, fishing and now the offshore wind industry would be the key drivers in GVA to EU economies. With offshore wind energy being quoted at €238 million GVA in 2010 and forecasted €40 billion in 2030, approximately equalling the shipping industry or that of all other industries combined, excluding the oil and gas sector. Understanding of the importance of including GVA in MSP was again seen in a sectoral policy assessment seen in [63] which identified this link and the need to understand spatial trade-offs. The work in [64] applied marine spatial planning to the value of offshore aquaculture and the impact industries have through growth. By assessing the spatial impact of competing industries, a relationship can be made for collocated spatial overlap. This concept of collocating offshore resources and establishing zonal values was further explored in [65]. Offshore oil and gas prospecting have long been the major focus of maritime industrial sector in Europe creating large areas of licenced marine zones for operation. However, not all zones are considered to be of the same importance with many licence grounds already sharing space with other marine stakeholders. Within the fisheries sector, assigning value to marine zones has often been carried out, as seen in [66] and [64]. In [67]catch weights were used to determine the gross value added GVA as a metric of industry importance.

1.6.5 Environmental Impact

Environmental factors, however, can vary due to the highly dynamic nature of the marine flora and fauna. These impacts are not based solely on obstructions but through the impact at stages from ground or benthic level through the water column to above sea level [68]. Although being highly technology dependant, common themes of regulation are evident. Notably, the environmental impact assessment (EIA) process outlines what consideration must be met to address affected stakeholders and aims to minimise loss [69]. Through applying the assessment criteria of environmental sensitivity, zones of significance can be focussed on. This method was observed in the EU NATURA 2000 study [68] of the impact of wind farm siting.

1.6.6 Electrical Infrastructure

The North Sea offshore grid (NSOG) has been identified as one of the strategic infrastructure projects for the EU with the idea of integrating offshore wind and markets for increased cross-border trade and cost reduction [70]. However, at an approximated cost of £130 billion, the benefits of such a system require critical analysis [71]. The work conducted in [72] explored scenario based analysis of forecasted renewable share, wind sector growth and cost. It was found that over the lifetime of projects cost savings could be made. However, the work failed to link the system into a spatial analytical platform allowing for the dynamics of site driven cost variability and subsequent energy market pricing.

1.6.7 European Energy System

In the past the European Energy system was fragmented into multiple groups with equally variable policy. However, over time these groups have developed into an interwoven system. Currently the synchronous grid of Europe is the world's largest and one of the most complex grid systems [73]. Over the past decade the associated infrastructure policy of the EU and national governments operating with the system have pushed to increasing cooperation to meet energy targets. The idea being that with a more diverse portfolio of cleaner generation being connected in a more dispersed market clean energy costs will be reduced [74].

There are smaller systems in Western Europe that show increased levels of cooperative infrastructure planning. This is seen in The UK and Ireland building new interconnectors and 'all island' approach to islands grid system [75]. Similar is seen in Denmark, Sweden and Norway whose combined approach has seen increased levels of Danish offshore wind being connected due to the increased demand in a larger system as well as the more flexible Norwegian hydro power. The partnered approach sees increased levels of interconnection being built across the system to expand cooperation [76]. The Iberian Peninsula is known to be an isolated part of the European grid system. Between the two countries there is a high degree of cooperation with multiple large energy 'corridors'. Although there is increasing support to better integrate the system in to the wider European system it remains isolated [77]. These systems are governed by national authorities or network system operators (NSO). At a high level of planning the combined grid systems NSO's form the European Network Transmission Operator Electricity group (ENTSOE). The group assess forecasts and develop cooperative cross border infrastructure planning measures to realise energy policy. The results of which are represented in the ENTSOE ten year development plan (TYDP). However, these high-level plans do not currently consider the requirements of future energy sources like floating WWE. Therefore, in order to address the future site suitability of floating offshore wind, the developing grid network must be examined in its relevance to the sector.

1.6.8 Grid Suitability & Site Selection

LCOE values of offshore renewables have large variations when comparing sites due to grid connection feasibility. When identifying future offshore wind sites in the UK, the national grid conducted connection studies to assess the cost and suitability of potential sites for development [78]. In order to make assessments, such as the 'round 3' auction sites for floating WWE, a link between coastal infrastructure suitability and the wider energy system must be made. The study into Baltic energy policy and offshore wind farm site analysis sought to merge infrastructure studies with spatial analytical requirements [44]. Similar was conducted in [79] which compared coastal resources against grid network models to identify sites of interest. The significance of matching the locations of high resource potential is a key issue when considering the current energy infrastructure, as has been seen in previously discussed curtailment of installed wind power. Studying the comparison of seasonal and diurnal variations in resource patterns and generation profiles provides an understanding of the suitability of sites for development. Variability in European renewable resources was demonstrated in [80] which highlighted the extremes across Europe. Figure 6 demonstrates the variability seen in the European grids across seasonal and diurnal time frames.

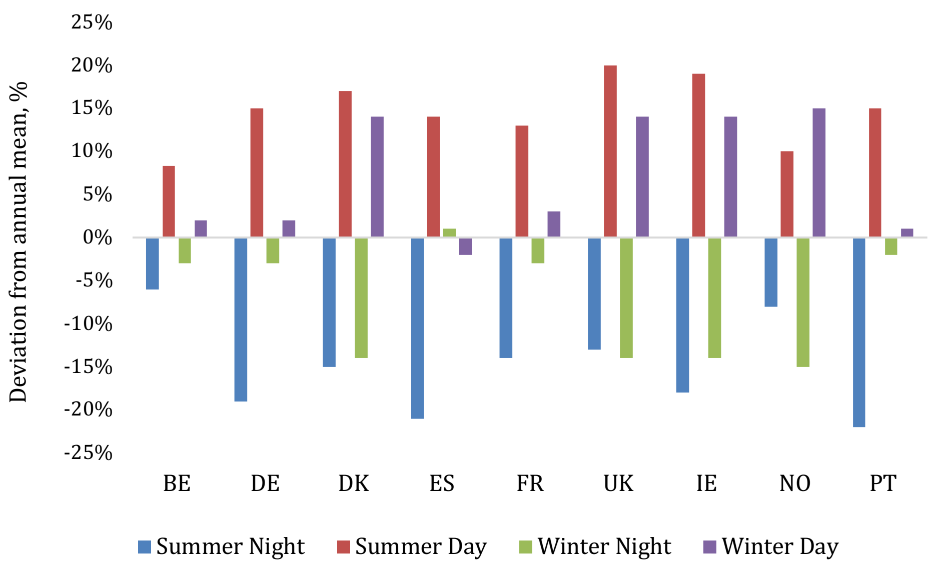


Figure 6. Seasonal and diurnal power demand variation in Western Europe varies considerably between countries [81]. Percentage deviation from the national annual mean demand, 0%. Extremes in deviation are found in the UK with the summer daytime power demand being 20% higher than the annual average.

The effect that resource variability has on wind generation and power demand was evaluated in [82]. Further work into the variability and uncertainty of wind power was seen in [83]. Although not limited to this work, the literature highlights the significance of variability. Work to optimise the mixtures of renewables is also one that is highly cited. The impact of large scale renewable mixtures in Europe where overserved in [84]. The potential for extreme loads and losses creates restrictions imposed on the current energy system. Similar work was seen in [85] which evaluated the role of what a flexible and storage-based grid would do for high wind penetration. The role of site suitability and variability is therefore a key challenge of this type of work.

1.6.9 Spatial Variability

Understanding how spatial variability can impact developments and grid patterns is another crucial link in site suitability. This was observed in the variation in wind farm power production the north sea was studied in [86]. The work utilised a spatial allocation modelling system to evaluate the impact that grid suitability could have on the cost of deployments for the North Sea by 2030. The work explored how configurations of offshore systems could be used to reduce cost for offshore wind. The work did not however, consider floating wind energy or wave energy. A Scottish government study and academic partnered research sought to address the transmission issues of connection future renewables through matching demand patterns and marine energy resources [87]. Representing the market variables that contribute to the dispatch of power has been represented through spatial analytics in a number of studies. The work conducted in [88]

[89] utilised spatial analytics to simulate renewable energy introduction through network topologies. Although robust, these studies did not relate the role of infrastructure development to the growth of future floating renewable deployments. Further they do not combine infrastructure analysis against offshore renewable growth at a local coastal or international level.

1.6.10 Grid Simplification

Simplifying a system as complex as the electrical network of Europe to represent a more simplistic set of demand, generation and transfer capability values requires a spatial reduction model. The significance of this kind of problem was identified in the e-Highway2050 project [42]. The Nomenclature of Territorial Units for Statistics (NUTS) region is a geocoded standard for spatial dividing geographical regions for statistical purposes. They are ranked in order of territorial significance with 0 being the whole country, 1 Regional boundaries, States or provinces and 3 minor districts. The e-Highway study, conducted by ENTSOE, used spatial analytical clustering techniques to identify the granularity of these socio-economic groupings for their relevance in infrastructure analysis. However, the level of granularity was not targeted at offshore renewables and therefore the role site identification has on transmission planning could not be explored.

1.6.11 Port Infrastructure

Ports are significant for their ability to perform certain key roles, either: installation, construction or maintenance for offshore developments. An installation port might involve a staging hub close to site where heavy machinery prepares devices for deployment. A construction port would describe a larger facility, requiring heavy manufacturing equipment. Maintenance ports might be smaller hubs with crews ready to quickly respond to failure [90].

1.6.12 Port Assessments

With many floating industry developments, the support system is similar to that of the fixed wind industry. To accommodate vessels and technology criteria assessments are conducted to establish suitability. The work conducted in [91] investigated the logistics capabilities of offshore wind ports, namely physical characteristics, connectivity and layout of the port for supporting various roles. Associated with each role are a set of criteria relative to operations. The characterisation of ports for offshore wind farm developments has been carried out for as long as there has been a development to service. However, knowing how to categorise these criteria in terms of significance in relation to a site is often drawn out and highly variable. The work, however, carried out in [92] developed an assessment method to take attributes and classify ports in ranked system. The relative significance of criteria was established through statistical modelling techniques and commercial engagement. The method utilised a case study as a decision-making tool to enable an assessment of suitability in the North Sea. The work in [90] applied a robust method to analyse the infrastructure requirements and targeting for wind ports in the USA. It utilised several case studies to apply methods to ports and highlighted weaknesses.

1.6.13 Port Capacity

A UK government report highlighted the state of market growth in the fixed wind sector. It highlighted not only the roles and requirements of infrastructure but also the competition and regional economic benefit of port activity. By creating regions of port coverage for expected developments it showed how the capacity of port infrastructure could be distributed. It highlighted the need to target policy to stimulate growth and economic value. Findings indicated the number of ports required to meet the demand from projects up to 2020 [93]. Spatial competition is crucial consideration for the floating industry as operations will have to work in partnership with existing work. It was identified in [94] that the wind industry might require increased port infrastructure development to meet 2030 targets

1.6.14 Port Requirements

Due to the similarities found in offshore wind and wave energy technologies certain conditions for port infrastructure remains the same. These include: the manufacturing, storage and handling facilities of ports and capabilities to accommodate a range of vessels [32]. However, for floating wind the joint study in [94] demonstrated variations in requirements. Including, the space and manufacturing ability required to assemble large mooring structures. In the case of wave energy a reduction in requirements could be observed as devices tend to be smaller and easier to handle [95].

The ORECCA project [53] on the status of offshore vessels and subsequent port infrastructure focussed on the offshore renewable industry's needs. It created a series of criteria for bespoke requirements. It further demonstrated how ports and vessels could be assessed and what forecasted trends to 2030 could be observed. The work in [96] identified the requirements for all floating offshore renewables technologies at a large scale. It further went into developing a screening process, as has already been done for the fixed wind industry, in determining the significance of attributes. It utilised case studies to address what regulation and policy might be required to implement effective change.

The requirements for ports are heavily tailored to vessel criteria. Vessel characteristics determine when operations can take place and to what port, for the case of large installation craft, they can berth. The differences in specific requirements or similarities between ports and technology was further researched in the European report on marine energy infrastructure [97]. The roles and readiness of infrastructure to accommodate growth was explored and the risk associated with infrastructure funding discussed. It is understood across the literature that targeting infrastructure will be a requirement.

The literature reviewed demonstrated key findings in assessing the research questions on port infrastructure. They demonstrate the roles and requirements demanded to satisfy sector growth. However, applying spatial analytical assessments to port capabilities remains a key issue. As was highlighted in [97] the need for lower risk assessments of industry potential is required for infrastructure development. However, the industry will be constrained by the lack of support. Therefore, determining that the two must be assessed in synergy.

1.7 Research Motivation

The assessment of the research background highlighted key areas in the research hypothesis that are lacking, they include:

- The literature examined a number of key site suitability assessment methods however these have not been applied to floating wind and wave technologies.
- The relevance of marine spatial planning and the spatial competition driven by spatial value for these energy sources has not been explored.
- Many site assessments consider port and grid infrastructure to be fixed point with limited values for practical assessment.
- LCOE mapping has been established for other industries, including wave energy, but not for floating wind.
- The sensitivity of LCOE to port and grid infrastructure for technologies has been briefly addressed but not at length and not for the floating industry.
- To assess how the combination of national grid capabilities into an energy partnership could alter LCOE and the connected capacity.
- Finally, but most crucially, the significance of each of these topic areas in combination has not been made. In order to make suitable assessments for large scale growth on a pan European scale each of these research gaps must be addressed.

1.8 Research Aims:

The thesis aims to expand the understanding of the influence of infrastructure on the achievable space and subsequent floating energy cost. Further to this, the thesis will also highlight the proposed method in which infrastructure can be modelled in a way to explore the potential for improvements. This aspect is especially important to consider due to the lengthy process of infrastructure development. In order to address these issues, the following research questions have been proposed:

1. What is the impact on sites for industry development taking into account mooring suitability?

2. Where are the optimum deployment areas from a resource perspective?

3. Considering other marine stakeholders where are the optimum sites from a marine spatial planning perspective?

4. Does existing port and grid infrastructure affect the selection of sites for exploitation?

5. How would infrastructure capability changes alter the overall deployment areas and associated costs?

6. Where are the optimum sites for strategic development and where should infrastructure be developed to satisfy the needs of developments?

1.9 Thesis Synopsis:

This thesis is organised into 10 chapters and associated appendices and is represented in Figure 7. Chapter 1 discusses the background to the issues surrounding infrastructure development and the objectives of the research. While chapter 2 presents a general overview of the methods adopted.

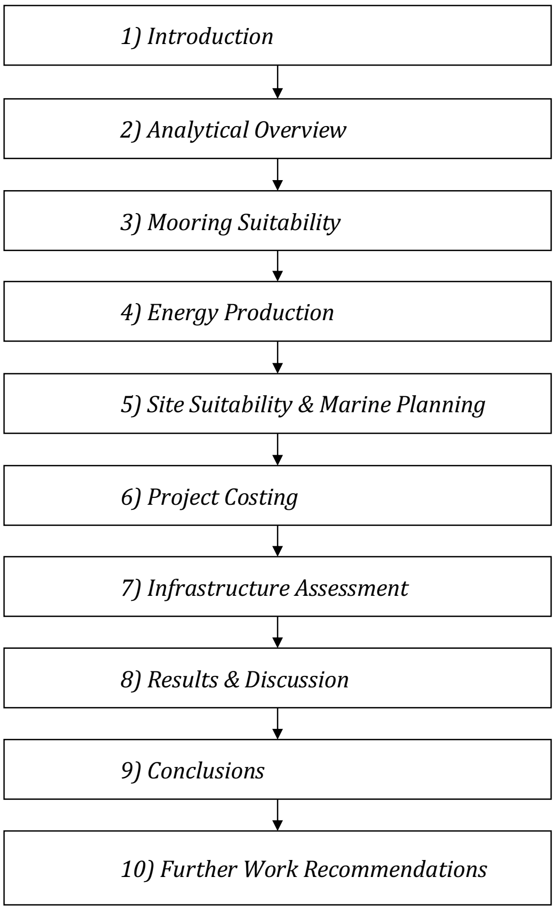


Figure 7. Thesis overview diagram demonstrating document structure with each chapter and topic.

In Chapter 3 – Mooring Suitability (considers *research question 1*). The mooring conditions and suitability for the technology types seen in the industry is assessed in this chapter. The technical characteristics of devices to maintain station the impact on site selection are addressed.

Chapter 4 – Energy Production (considers *research question 2*). Demonstrates a method to evaluate the potential energy extraction from key technology types for floating WWE. Resource assessments and performance of device arrays is established through a series of spatial analytical models.

Chapter 5 – Site Suitability and Marine Planning (considers *research question 3*). The spatial competition with other marine stakeholders, including environmental impacts, that could arise with large scale array developments is addressed in this chapter. The role of marine spatial planning is examined, and novel methods are applied to floating WWE.

Chapter 6 - Project costing (considers *research question 4*). The role of site driven cost factors that may arise from infrastructure modelling is examined. This chapter demonstrates the techno economic variables and spatial modelling techniques that employed to conduct such analysis.

In chapter 7 – Infrastructure Assessment (considers *research question 5*). An iterative spatial allocation method is demonstrated which seeks to identify locations of infrastructure in relation to potential sites. The focus of infrastructure allocation for floating WWE is aimed at a sub national coastal region granularity. To assess theoretical levels of floating power injection a series of spatial and electrical models are outlined. Two analytical methods to assess infrastructure capabilities relative to the allocation modelling. A genetic algorithm assesses the practical limits of connection to the Western European energy system while a spatial analytical model considers the time taken to achieve such deployments.

Chapter 8 – Results and Discussion (considers *all research questions, including 6*). This chapter presents the results of the work from each analytical method. It evaluates the impacts of the scenario-based outcomes for varying forecasts and policy formats in relation to infrastructure and LCOE modelling. The relationships between scenarios and types of targeted infrastructure policy is assessed for its impact on cost and the growth of the industry.

Chapter, 9 – Conclusions. This section concludes the body of work and identifies the relationship between the current infrastructure trends and the desired approach that should be taken for floating WWE success. The final chapter, 10, identifies work which could expand the depth and application of this thesis to further add contribution to the state of the art.

2. Analytical Overview

Abstract: Chapter 2 presents a general overview of the methods adopted, flow of modelling between sub models and major datasets used. Further scenarios to be explored by the tools developed are outlined. Forecasted trends in infrastructure development and energy patterns are described for their significance to the overall modelling.

2.1 Geographical Scope

The resource potential presented in Figure 5, demonstrated greater intensity on the Western Atlantic coast and the North Sea. Unsurprisingly, the technology maturity and research in these types of energy are found in these countries with developments in floating wind and wave taking place in these regions. The level of interest of floating technologies is therefore found in these countries and therefore development is considered the most likely in Europe. Therefore, this focuses on the European countries of the North Sea and the Western Atlantic coast. Figure 8 illustrates the area that this research focusses on and the respective nation's marine zone or EEZ. The Norwegian EEZ has been halved to represent the southern portion of its marine zone. This is due to data access constraint identified prior to the modelling processes.

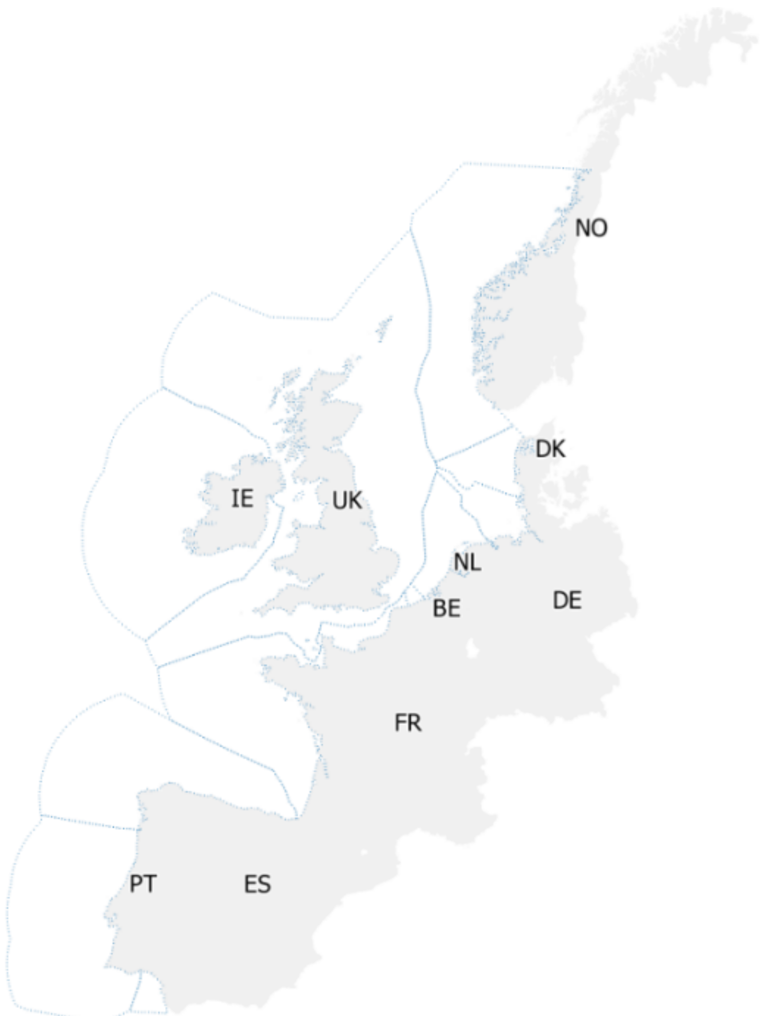


Figure 8. Study countries and respective EEZ boundaries, marked by blue lines, selected for analysis. PT – Portugal, ES – Spain, FR – France, BE – Belgium, NL – Netherlands, DE – Germany, DK – Denmark, NO – Norway, UK – United Kingdom, IE – Ireland.

2.2 Analytical Methods

Models are constructed around a set of geospatial analytical tools established in a geographical information system (GIS). As was outlined in the literature GIS in offshore renewables, as well as other industries, is becoming an increasingly more popular method for spatial analytical assessments. GIS enhances the ability of a user to present and analyse multiple layers of data. Datasets can be combined to establish complex multi-layer analytics and present output in a map format. The level of analytical process is expanding due to the ability to create bespoke modelling scripts and tools to conduct analysis. A full list of all data utilised in the work has been compiled in appendix I in 12.1.

2.2.1 Software Selection

There are a number of analytical tools which could have been applied to the data. They fall mainly into two forms, open sourced and commercial and is dominated by two main software types QGIS and ARC GIS. While open sourced software, most notably QGIS, a python-based package has expanded usability due to the greater range of exploration and manipulation of code. This expanded range of possibilities allows for more bespoke operations to be conducted and tools created. However, QGIS lacks a wide range of pre-determined tools and requires considerable script editing for functionality. ARC GIS has reduced scope for unique coding but has a wide range of user friendly intuitive geospatial tools with some scope for integrated coding. ARC GIS has industry leading spatial analysis toolkits which are equipped with spatial technologies designed conduct network analysis. Network analysis functions allow for the assessment of problems to be addressed in the thesis. The version of GIS, ESRI ARC GIS, was applied in this thesis to conduct modelling work and integrate modelling techniques tailored to infrastructure analysis. The software utilises a version of python, ARC PY, to allow users to integrate some level expanded analytical processes, although it is not as flexible as QGIS.

Data base management, cleaning and analysis was conducted using Excel for Visual Basic Applications (VBA). VBA is an event driven programming language that is integrated into Excel and can be used to customise tabular based analytics. VBA Excel and Excel macros offer the ability to record operations conducted in Excel and edit the associated script to expand functionality. The scripted macro allows for faster manipulation of data without human error. However, the language does not connect to python or GIS and therefore presents a break in what could otherwise be automated in other coding languages, such as python. This also presents a need to learn two types of coding language rather than one. However, owing to the ease of macro recording this issue can be negated. Furthermore, as it is beyond the scope of work to create a unified tool for analytical purposes there is no need to code in one language. Within this work VBA macros and models were applied to datasets in this thesis and its application and method is noted where required.

2.3 Spatial and Temporal Resolution

The geospatial modelling process takes either raster or vector data to form a layer of analysis. Vector sets, including points, lines and polygons are statistical datasets with spatial conditions. The second, a raster, being a regular mesh of cells to form a mosaic values, most commonly used to represent concentrations and surfaces. Working between the two is known as a process of rasterization, as demonstrated in Figure 9.

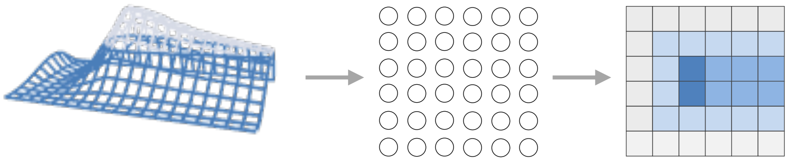


Figure 9. Example process of rasterization of resource and subsequent performance variables to a point matrix to raster cell lay

2.3.1 Spatial Matrix Resolution

Within the EEZ of the study area a spatial distribution point matrix contains data pertaining to each layer developed by the analytical models. This matrix is restricted by the computational constraints of modelling as well as a minimum representation of features. Due to computational constraints it was found that a resolution of 2km was most workable while allowing for representation of geographical significance, with a total marine zone point count of approximately 800000. Larger cell sizes, above 2km, where considered to reduce computational at the expense of a loss in granularity. However, the impact was deemed too severe resulting in a loss of ability to detect coastal features. Smaller defined matrices of 0-2km over the study area breached the boundary of the software's handling ability. Similar assessments have been made with a 2km spatial matrix resolution utilising ARC GIS in the work of [87].

2.3.2 Temporal Resolution

Temporal resolution was established as an annual mean for all spatial models over projected time frames of 2018, 2020, and 2025 to 2030. The 2030 time frame was established as it represents the energy target set by the EU and partner member states being studied in this thesis. However, the work could be expanded to project further with new datasets in future. The temporal resolution for grid sensitivity assessments was expanded from the annual mean to a seasonal, summer and winter, and diurnal, day and night, mean granularity. As discussed in the literature this temporal representation was established to provide more detailed understanding of the relationship of variability and site suitability.

2.4 Modelling Process

Multi-level modelling approach was applied to resolve the research questions with a focus to representing the spatial relationships of LCOE and industry development. An overview of the modelling process is represented in Figure 10 where spatial analytical models are resolved with infrastructure scenario inputs.

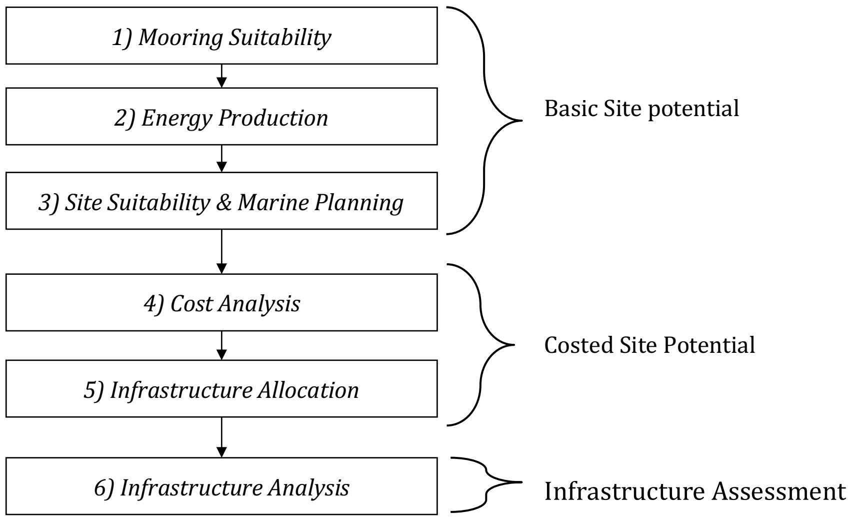


Figure 10. Modelling flow process of 6 modules achieving 3 stages of assessment.

The modelling flow outlined is comprised 6 modules that constitute three topical groups. Basic site potential encompasses the technical and marine spatial planning requirements to create a suitability map for use in the costing and infrastructure allocation analysis. This second site potential demonstrates the infrastructure utilising theoretical limits. The last stage, site selection, considers the practical limitations of infrastructure and outputs a series of development options. The modules are comprised of multiple sub models and tools used as follows:

1) *Mooring Suitability*: Two technology types are assumed and used in the analysis. Mooring criteria are assessed and the mooring suitability estimated for geological, depth and geotechnical limitations. Suitable locations are chosen for further analysis,

2) *Energy Production*: Resource data and technology characteristics are used to establish performance across cells in the study area. The performance is approximated for costs analysis at an annual level but also at a seasonal and diurnal level for infrastructure modelling.

3) *Site Suitability and Marine Planning*: Resource, mooring suitability and environmental sensitivity are integrated into a suitability layer. This is established through the application of a weighted assessment in an MCMD analysis where further layers of other marine users are assessed. Constraints area removed and remaining areas are filtered to identify zones for suitable deployment. Statistically significant regions are grouped and provide a zone of development and the 1st site potential distribution.

4) *Project costing:* Examines the driving factor in the site selection process and infrastructure analysis. A cost analysis module establishes the LCOE for each cell. A comparison of LCOE being constrained by the location of known infrastructure points and not constrained by

any location is assessed. The relative sensitivities of LCOE and locations suitable cost sites are discussed.

5) *Infrastructure Allocation:* The established zones of development from the proceeding spatial models are used to score cells. First a minimal 'facility allocation' algorithm seeks to find the optimal distribution of array points to centralised substations of an approximate range of size between 100- 800MW. The second algorithm, maximised 'capacitated coverage', assigns the maximum number of array groupings to candidate port and grid connections based on their relative capacity. Infrastructure scenarios for both grid capacity and port suitability are evaluated. Infrastructure is first allocated suitable grid capable locations with the lowest LCOE. The resulting array locations are then allocated a suitable port connection. A cost analysis module establishes the new LCOE for each site being constrained by infrastructure. These cost and infrastructure constrained sites provided a 2nd site suitability distribution for analysis.

6) *Infrastructure Analysis:* As discussed, the capability of ports and grids to accept the allocated volumes of power is assessed in this analysis. Here port handling is assessed for its ability to move quantities of technology to site. The travel times are assessed for the ability to conduct the required number of operations. In order to represent the spatial impact of floating wave and wind energy on the grid a genetic algorithm model considers the variability in power supply, nodal grid connection and wider grid demand and generation capability to accept volumes of power. By doing so the role of resource variability on site selection and energy penetration will be exposed. The infrastructure-based influences will be assessed for the 3rd and final site potential providing a selection of development zones.

2.5 Scenario Analysis

Due to the nature of the type of analysis proposed in this thesis being over a large study area with a large number of variables a series of scenarios for analysis were created. These are designed to establish key relationships that will provide solutions to the research questions. The following scenarios and case studies are proposed to assess growth of technology deployments and limitations of infrastructure.

2.5.1 Industry Growth

The first scenario-based analysis seeks to demonstrate the location of potential future industrial growth based on cost reductions. If growth continues without infrastructure development certain location-based bottlenecks could occur. Therefore, a series of hypothetical forecasts for 2018 and 2030 are modelled in relation to current, 2018, infrastructure locations and capacities. By doing so the constraint of infrastructure on growth can be contrasted.

2.5.2 Infrastructure Forecasts

Electrical forecasts have been made to highlight the impact of new generation to meet targets to 2030. However, these have been aimed at current technologies and may be satisfactory for floating technologies. Similar has been observed in port development where several key port expansion projects are due to take place. Therefore, simulations are carried out in the VBA and GIS models for progression over time across 2018, 2020, 2025 and 2030 to demonstrate whether these improvements will be beneficial for the industry.

2.5.3 Infrastructure Partnerships

While it is understood that not all nations within the geographical scope of the thesis will combine resources there are several key energy partnerships that could be considered likely. Modelling will solve to distribute cells to a unified grid connection system rather than an individual country. The partnerships types that will then be explored are represented in Figure 11.

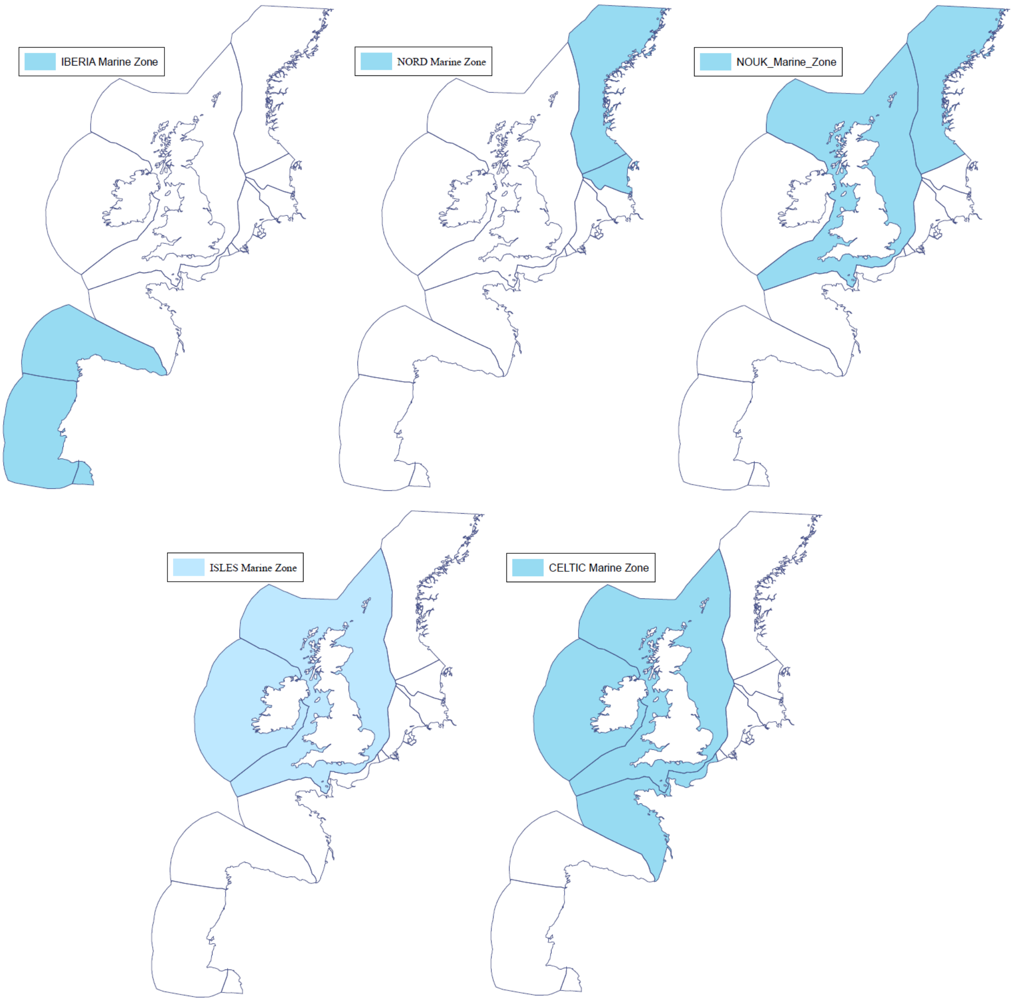


Figure 11. Energy partnership group marine zones, from left, IBERIA, NORD, NOUK, ISLES, CELTIC. Highlighted in blue are the combined EEZ search areas used for analysis.

These partnerships are aimed at identifying whether collaborative infrastructure policy unions could provide cost reductions for 2018 and 2030 time frames. Each of the partnerships have, in the past, demonstrated clear policy collaborations in energy developments in the past in practise and the studies seen in the research background in section 1.6.6. Infrastructure analysis is conducted on each of the scenarios to assess the relative impacts of forecasts and simulations. Those areas identified as highly suited for development are assessed. While those sites that show high potential are assessed in a series of development case studies. These case studies will demonstrate the impact of upgrading or developing new infrastructure to support technology growth and reduce LCOE. At the time of writing the political landscape regarding the UK and its membership to the EU was in question. It was conceptualised that this scenario of the UK's exit from the bloc, colloquialised as 'Brexit' could be assessed using the analytical tools set out in this work. This has been expanded on in more detail the further work Section 10.

2.6 Research Objectives

The models are based around two technology types to reflect the wave and wind industries as well as fixed port and electrical infrastructure configurations. Further the outcomes are addressed as a series of hypothetical strategic development scenarios based on the most up to date and available data as off 01/2019. Due to the scope of work being aimed at such large geopolitical area encompassing multiple nations, not all of which are EU member states, considerable effort was made to create robust datasets to perform analysis. Although, currently, the most relevant data available was sought after it is understood that new information may change results. By creating development scenarios, the models demonstrate a relationship between cost, infrastructure and policy strategy. By targeting key areas, the models can highlight the most beneficial areas for focused development. Therefore, the objectives of this thesis are too:

- Develop a spatial analytical system capable of conducting multi-level analysis on technical, economic and geographical datasets.
- To assess the impact of marine spatial planning and marine management on site selection
- To examine the site-based cost drivers and their relationship to infrastructure.
- To develop a series of spatial analytical models designed to allocate potential sites to suitable infrastructure and assess the impact of cost.
- Through the application of spatial data to infrastructure analysis models assess how suitable Western European infrastructure is for floating wave and wind technologies.
- To address the role political partnerships in both grid connection and maritime zoning has on site suitability and project development.
- To create a system that could be adapted for multiple types of floating wave and wind technologies as well as modified datasets.

Using the methods established to evaluate research gaps and questions the thesis will be used to formulate an outline for policy framework. This will seek to assess the strategic development of the supporting infrastructure for floating wave and wind technology. This will demonstrate research needs to conduct further analysis into policy development in energy and infrastructure strategy.

3. MOORING SUITABILITY

Abstract: In Chapter 3 mooring technology assumptions are made to represent the floating wave and wind industries. The geotechnical characteristics of the seabed are examined. Further, limits of mooring ability for devices are assessed for the study area. This forms the first element of the basic site suitability.

3.1 Introduction

In the past, a key reason for the problematic development of offshore renewables has been the engineering challenges faced. The footprint of fixed structures involves several limiting technical factors that impact site selection which require uniform seabed conditions with minimal variability. Sites can be excluded if they include variable slopes and elevations in bathymetry and shifting geological makeup resulting poor conditions. Floating technology however has the ability to negate many of these factors through the use of mooring lines and anchors [18]. A combination of geo spatial mapping tools has been exploited in to answer the first research question:

1. What is the impact on sites for industry development taking into account mooring suitability?

3.2 Modelling Overview

A mooring suitability was established from the combination of slope and geological characteristics based on common engineering practises for floating technology. A full list of all data sources can be found in appendix 12.1.1. Each cell in the study area was assigned a suitability value and optimal cells scored best. Cells with extremely poor traits, including extremes in depth, slope and geological fault were removed from the analysis. Removal was performed in ARC GIS using a suite of spatial analytical tools which are referred too when appropriate. Although it is known that met-ocean parameters have an impact on site selection it fell beyond the scope of this thesis to carry out such analysis. An overview of how this work could easily be integrated into the model has been presented as further work in section 10.

3.3 Technology Characteristics

Exploiting the resource available is highly dependent to the characteristics of the technology in question. As characteristics are unique across the industries of floating wave and wind, a device assumption was necessary. Two technology types with established potential were chosen as reference devices owing to more readily alliable data and the progress being made at the time work was conducted.

Floating Wind: Although currently the industry has performed successfully using 6 megawatt (MW) devices, future deployments are expected to be at 8MW and possibly larger still [98]. Therefore a representative 8MW wind device has been selected and its characteristics obtained from [99]. The support structure for the floating wind device modelled has been selected as the Spar Buoy. While other types, including semi submersibles were considered, this form of floating structure was chosen due to the ease of access to available technical data owing to its maturity. This being due to the level of technology readiness with commercial projects online with the Hywind farm.

Floating Wave: Although, as discussed, many types of wave converter are under development, and some having reached full scale development, there is currently no full scale commercially viable wave energy converter. Therefore, a demonstrative 1MW device was selected as the rated capacity most likely to be seen at commercial scale at the time of writing, a similar approach was seen in [87]. In this thesis, a heaving plate absorber similar to that of the OPT device has been selected [26] achieving full scale status to 750kW.

3.3.1 Physical Properties

The physical dimensions that will impact the array configuration and the resource extraction estimation are represented in the technology schematics in Figure 12. For the wave device this includes the draught or subsea surface length of the structure and the excitation or movement of that structure in relation to wave forces. The wind device includes two key above sea surface characteristics including the diameter of the swept area of the blades or rotor and the distance to the nacelle or 'hub' connection of rotor to main support.

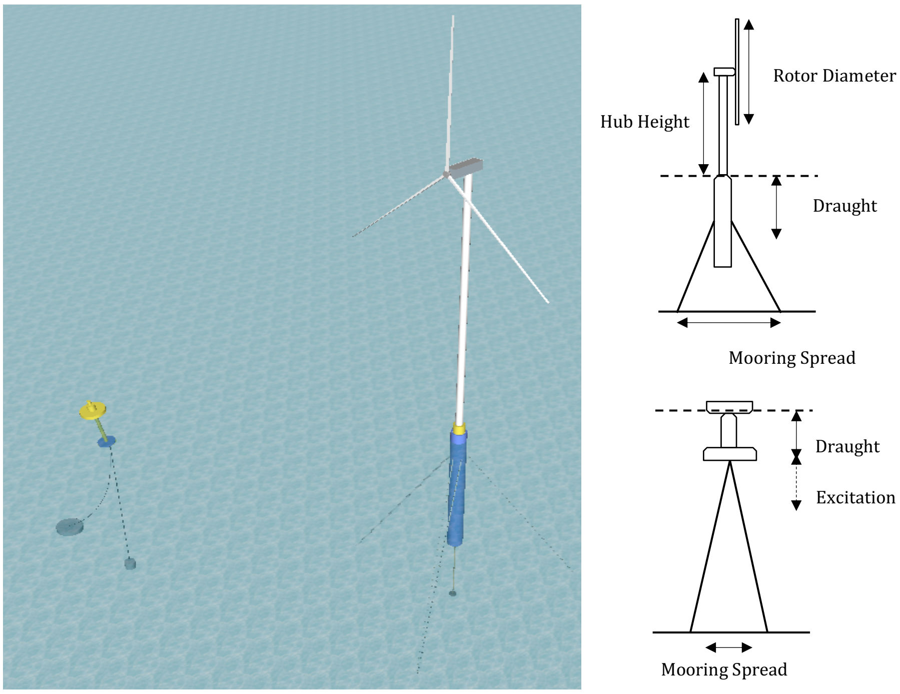


Figure 12. Representation of reference technology types in the marine environment (left). Representation of key dimensional properties for both devices, floating spar buoy wind (top right) and heaving point absorber (bottom right).

For the 8MW wind turbine the characteristics are assumed from the reference literature in [99]. The device has a diameter, D, of 164m and the hub at a height, h_{hub}, of 110m. While the floating support structure being examined in this case is the spar buoy, it has a draught, d, of 60m and a minimum water depth of 70m [18] and [100]. The wave energy converter used in this thesis, the OPT power buoy is assumed to have a width, D, of 10m and a draught, d, of 15m. However, the minimum water depth for the wave converter is also influenced by the device's key generation principle of plate excitation.

Design features of the wave devices in [101] were assessed, and the combination of mean draught and approximated heave excitations converged to require a minimum depth of 30m [102]. Depth limits have been capped at a maximum 1000m four times the preliminary industry estimates with most future projects being quoted at 100–300m, while existing projects are sub 100m [103]. At the time work was being conducted a market review of floating wind technologies [104] also listed the most advanced design types having a reported depth cap of 1000m. This limitation is understood to have a significant impact on site selection owing to the depth of the Atlantic coast and further iterations of this modelling process could be used to explore further depths. However, for the purposes of this work and the nascency of the technology development beyond 100m this limitation has been assumed as suitable.

3.4 Spatial Suitability

3.4.1 Bathymetry

Bathymetry data was obtained for the study area from the European Marine Observation and Data Network (EMODnet) [105] at a resolution of 0.00208 degrees, approximately 230m. This spatial representation being the smallest resolution available for a continuous dataset across the study area at the time. The data has been presented, in Figure 13, for both technology types and associated depth limitations.

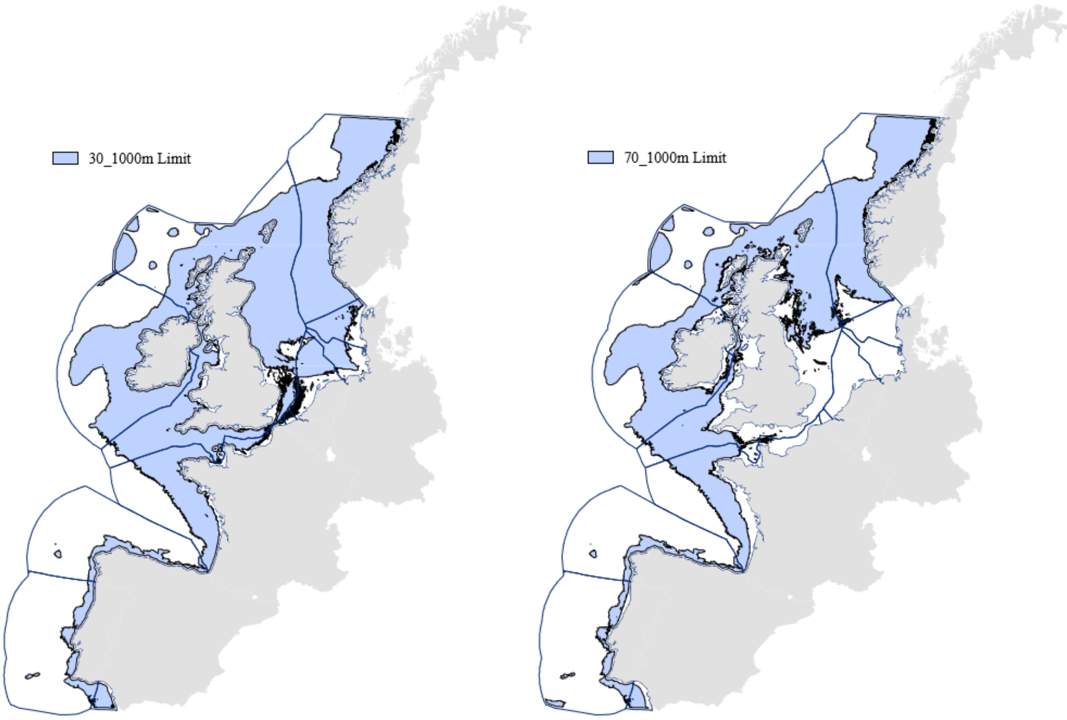


Figure 13. Study zone process area after bathymetry depth limitations for wave (left) and wind (right).

3.4.2 Slope & Geology

Bathymetry was obtained from EMODnet at a resolution of approximately 230m. A slope calculation was used to assign gradient change between cell neighbours. The tool fits a vertical plane in the data set of a 3 x 3 matrix neighbourhood around the central cell of raster and works on the change to its eight neighbours.

In accordance with common spatial analytical practise it is necessary to correct the vertical units, elevations in bathymetry, against the horizontal units. Adjusting X/Y data for coordinates is required to represent plainer measurement onto a spherical coordinate system. If not carried out for vertical units latitudinal shading, or an extrusion of vertical representation is caused by the 'wrapping' of data onto the spherical coordinates system. The impact is a poor GIS representation of slopes [106]. A mean z factor of 0.00001171, 0.00001395, and 0.00001792 was applied to the slope estimation for the extreme south (40 Degrees), centre (50 degrees) and north (60 degrees) latitude. These values are standardised for their global position which was observed in [106] which discussed this cartographic representational issue. Figure 14 illustrates the slope conditions estimated across the study area.

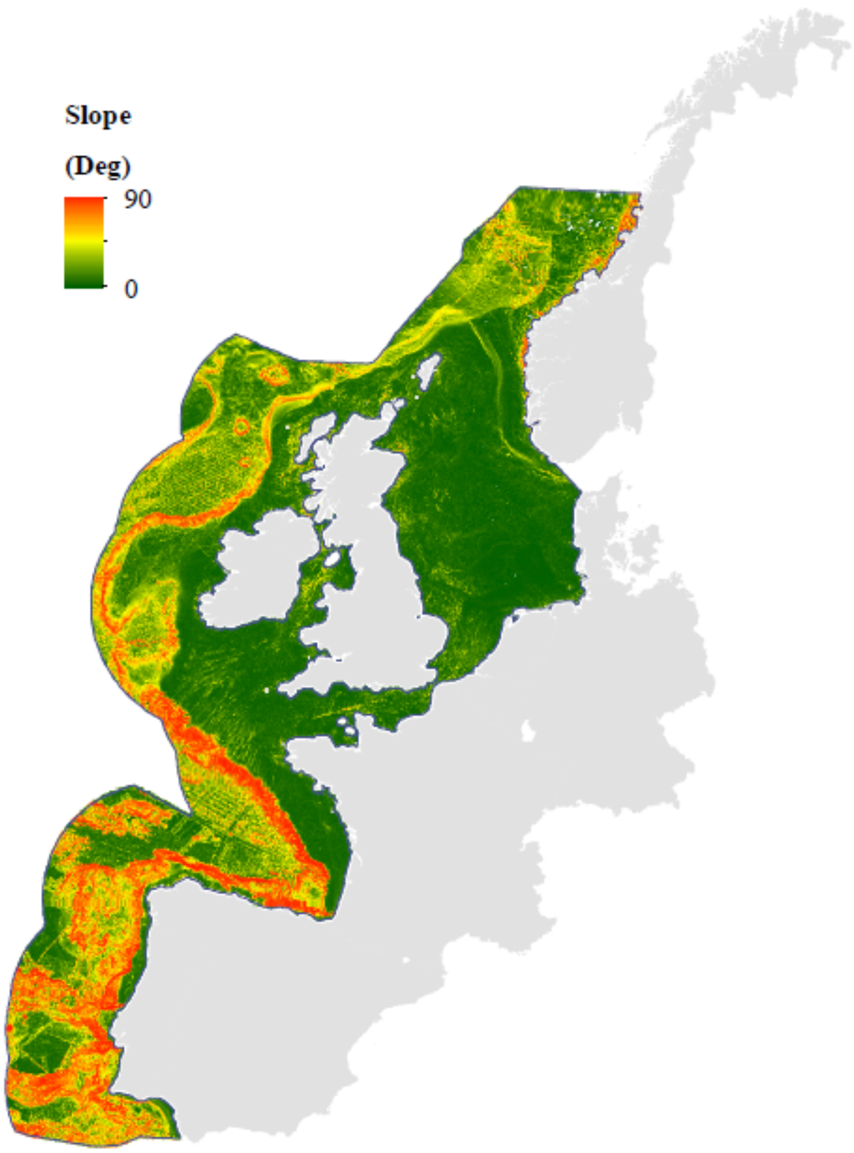


Figure 14. Approximated seabed slope angle with green regions being most suitable for mooring and red worst.

The seabed slope angle approximated demonstrates the relatively flat areas in contrast to those of extreme slope angle. As expect the Atlantic ridge is visible with high slope angles at almost a shear 90 degrees while the North Sea remains flat. The geological substrates identified on the seabed range predominantly between mud and sand while several instances of hard rock or coarse gravel where present.

3.4.3 Mooring Configurations

Mooring systems have a high degree of site dependant characteristics that can impact suitability. Subsequently, multiple variations of systems are possible for these types of operations which is usually based on ease of installation, cost, and load suitability. Without conducting detailed loading analysis caused by the floating body drag and inertial load a best cost solution was not possible. This topic has been explored in more detail in the further work section 10.1.2.

Therefore, the assumption has been made towards the most likely configuration for the deep-water floating wave and wind technologies. The European Marine Energy Centre (EMEC) program on to the reliability and suitability of ocean mooring types demonstrated that a taught or semi taught multi point chain mooring system would be most suitable for large deep water technologies with either suction or drag anchors [107]. Similar was identified in [53] [108] for the technology and the common systems used in the study area site conditions. As the spar buoy technology is already in operation it has been assumed that a similar type of multi-point system would be used. The same has been assumed from [109] for wave. Furthermore, multipoint systems also have an adaptability that allows for more flexible configurations allowing for wider adoption in more variable seabed conditions. A representation of the system types is demonstrated in Figure 15.

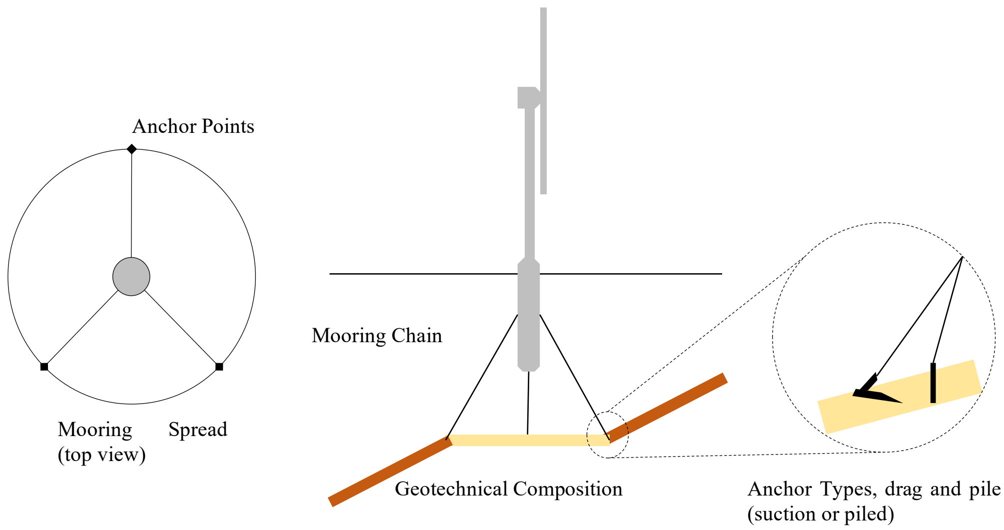


Figure 15. Three-point configuration mooring assumption and anchoring types plan view (left) and cut section anchor view (right) for the example of floating wind turbine.

The conditions that might determine suitable deployment of such systems of slope, depth and seabed geology are combined to form the mooring suitability. A three-point 'generic' connection to seabed anchor mooring configuration have been chosen for both types of device. The 'generic' assumption is a cost factor considered in section 6. While assumed mooring characteristics for the multipoint system are applied to the GIS datasets, they only impact cost due to depth. The configuration between device and anchor is known to have an impact on design, functionality and cost particularly in relation to wave devices. However, it is not the purpose of this work to evaluate these characteristics and the assumption does not impact the assessments made in this section.

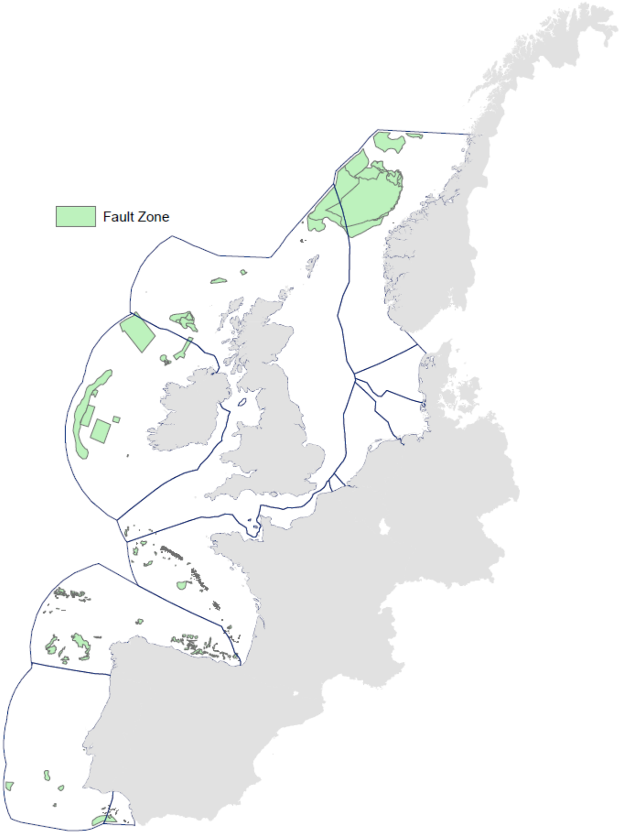
3.5 Mooring Complexity

As discussed, the combined conditions will impact the technical feasibility of the mooring configuration. An industry technical appraisal and guide to anchoring for the types of mooring fixtures considered [110], anchors and suction piles under semi taught loads, have been used to develop a mooring complexity matrix, Table 1.

Table 1. Mooring complexity index, where 0 is the most suitable or least restricting and 7 the most restricting with the highest form of mooring complexity according to the 2010 anchor manual by industrial specialist Vryhof [110].

Slope (Degrees)	Sand	Mud / Till	Mixed Sediment	Coarse sediment	Hard Rock
<10	1	1	2	2	3
<20	2	2	4	4	5
<30	3	3	5	5	6
<50	4	4	6	6	7

The most severe limitations where set those substrates that are comprised of hard bedrock and are at extreme angles compared to flat sand or mud. Each cell in the study area was assigned a combined value to determine site suitability. However, some areas of the seabed are fundamentally unsuitable due to geological faults. In Europe there are a number of locations where subsea landslides and instability are regularly observed and a probability over a particular area can be estimated. These conditions usually occur near shear sloped shelf zones and/or areas of loose substrate. An EMODnet dataset, *'Submerged landscapes - geological risk regions'*, was used in analysis to determine the location of such high-risk areas. The faults represented in the EMOD data can refer to: sediment mass movement under load, avalanche, landslides, creeping falls, gravitational slope deformations, rock falls, high topple/slide/shift possibility, rotational shearing and areas of critical erosion. These high-risk fault zones are presented in Figure 16 respective to the study area as well as the final mooring complexity.



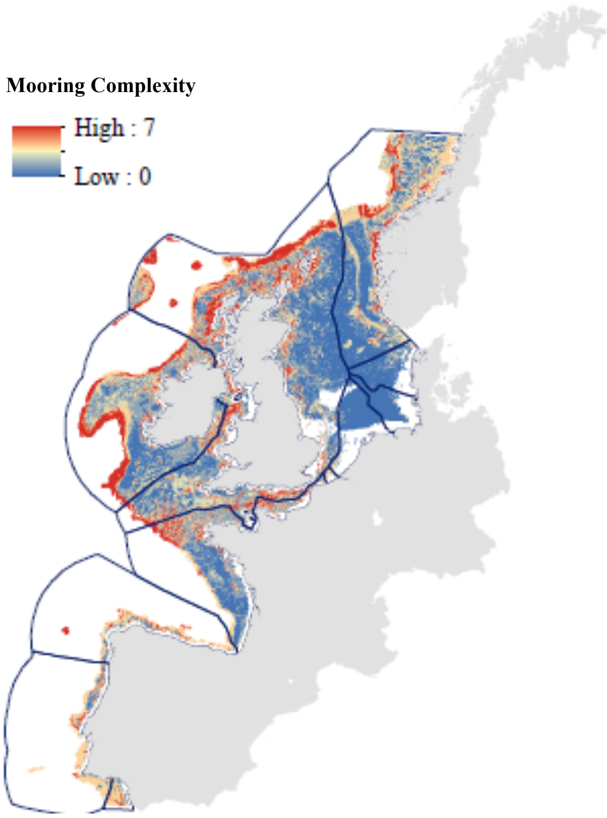


Figure 16. Subsea geotechnical fault zones (top) mooring complexity scored 0-7 where high values are worst (bottom) clipped between 30 – 1000m (bathymetry extremes).

Present in the study area are large fault zones that have been determined unsuitable for operation. These fall largely beyond the maximum depth of 1000m due to their relative position along the Atlantic ridge. However, several instances near the coasts of Norway and Spain have significantly large areas of fault. These areas have been removed from the study area. Of the remaining sea zone, the cell matrix has been rasterised to demonstrate the distribution of mooring complexity. As expected, the combination of slope and geology have impacted the regions approaching the continental shelf.

3.6 Chapter Summary

As discussed, mooring suitability has been considered in this thesis for two technology types. While the focus of this work was to explore the potential of the industry it was necessary to make approximations due to the limited scope of this work on the subject of mooring suitability. As such limitations of the work were observed in the assumptions into mooring configurations and the impact on site selection in the following models. Although, mooring types could be designed to operate in a wider range of sites, this work represents the assumed configuration as favourable for mass roll out. The selection of commercially viable technologies and representing their requirements at this stage in the analysis has therefore created a crucial analytical step in site selection. The converter technology and station keeping configurations will dictate the power production and site suitability in the following models.

4. ENERGY PRODUCTION

Abstract: Here a method to evaluate the potential for energy extraction using the converter technology is discussed. The spatial modelling process to establish power production is outlined and forms the second element of the basic site potential. Resource assessments are examined and the performance of arrays of devices is explored for a temporal representation in the study area.

4.1 Introduction

Naturally the primary driver in site selection for renewable energy technologies is the power production from the resource in question. For floating wind this is determined by the availability of favourable wind speeds at to the rotor centre, or hub of the device. For wave energy technology it is determined by the availability of suitable bivariate combination of wave characteristics, wave height and period. Directionality for both technology types has an impact on array production. This is not only due to the absorption of energy by the converter but also the array interaction with surrounding devices. The significance of the quality of resource is to therefore determine how wave and wind climates will suit the technology's power production in an array. The mapping of the resource and subsequent energy production will provide the first layer of preliminary results and answer the second research question:

2. Where are the optimum deployment areas from a resource perspective?

4.2 Modelling Overview

The process of establishing energy production values were found using a combination of spatial and numerical modelling techniques. ARC GIS established the spatial relationships of the data. A series of analytical techniques to bin and filter data was applied in VBA Excel which conducted hindcast analysis and data cleaning. Energy production was established for each cell in the point matrix as described in Figure 17 in GIS using a series models to perform study area wide analysis.

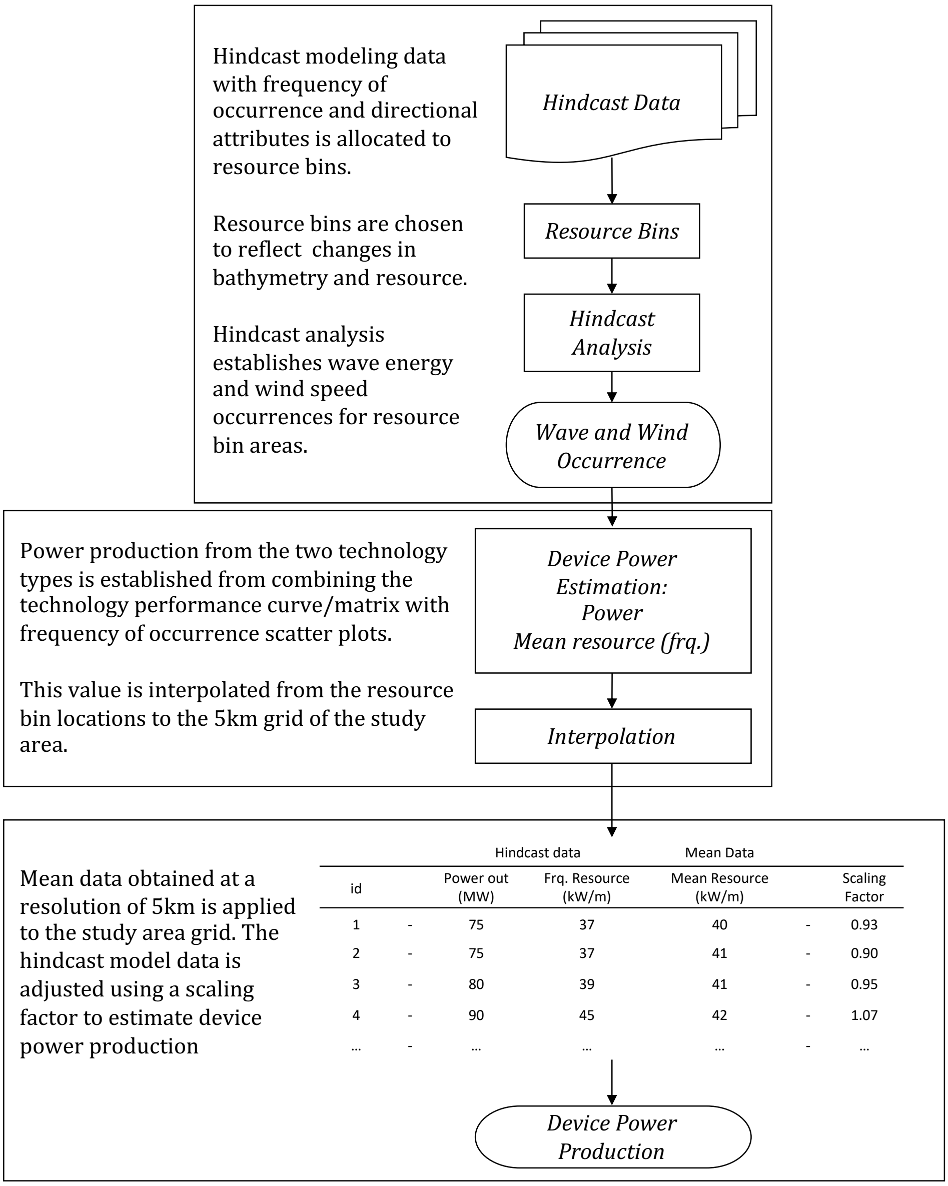


Figure 17. Modelling flow process of energy production for the study area matrix.

Hindcast data was provided with other datasets as described in the following section. The overall process illustrated demonstrates the contributing datasets and variables assigned to each cell in the point matrix. This provided an annual energy production value used in spatial modelling, as well as, seasonal (winter and summer) and diurnal (day and night) average energy production values used in resource suitability assessments in latter modelling stages.

4.3 Resource Data

The resource characterisation was established from data [28] provided by the University of Athens at a spatial resolution of 5km with an hourly temporal resolution over 10 years (2001 – 2010). A list of all the data used is compiled into the data sources table in appendix 12.1.1. The data was compiled using a series of high-resolution modelling system and is validated against historic data. Associated with the 5km data set is an approximated water depth although a more refined bathymetry will be used further in this study, as outlined in section 4.7. Due to computational expense, annual, summer and winter mean values were used at such a fine spatial resolution. From the model data seasonal, winter and summer mean values across for each 5km point were extracted and used in the analysis. While no post processing was carried out it is assumed that for the purpose of this work, representative data is adequate. The results of this work are intended only to demonstrate the interaction between models in the aim of exploring wave and wind technology infrastructure requirements. However, a coarse resolution of hourly data was applied to key points, or resource bins, as outlined in section 4.3.1.

4.3.1 Hindcast Resource Data Bins

The hindcast data provided was selected from key representative points established from the needs of the modelling work. Data points were based on the relationship of both distance to shore and mean resource characteristics. The ARC GIS tool, *Reduce Point Density*, is typically applied to depth and bathymetry datasets. The tool creates a spatially biased output based on the range of surrounding neighbour points to represent locally significant extremes in variation. However, the principle of thinning remains the same for the identification of extremes in resource variation. A brief summary of the process is outline in appendix 12.2. The output, Figure 18, represented the bins in relation to the finer 5km resource data set where wave and wind are combined.

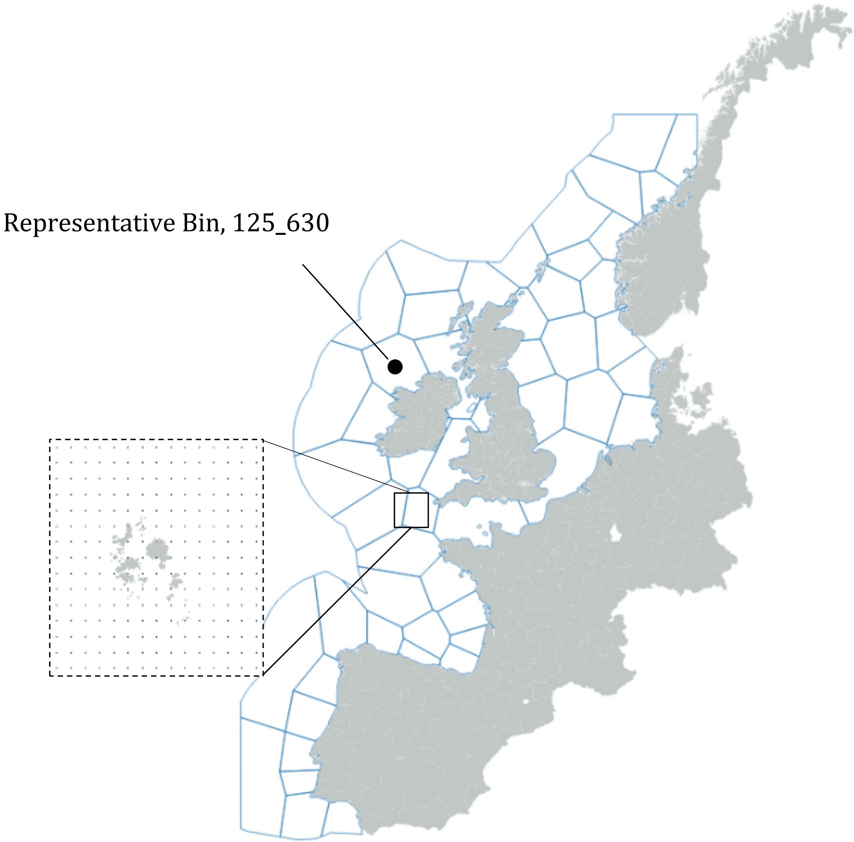


Figure 18. 52 combined resource bins as represented out of 201400 data points.

The resource point selection process established groupings that were a set distance to extremes in resource variation over a fixed distance. Although representing points over such a vast area would include errors, due to changes in bathymetry or meteorological factors, it is assumed to be minimal. This is due to the minimum depths being assessed and the minimum distance from shore outlined in appendix 12.2. Interpolation methods used were deemed to be suitable for regions not in the nearshore region. As technology assumptions will focus site selection into deeper water, this assumption has been deemed suitable.

4.3.2 Wave Power Estimation

When winds pass over the ocean, they create waves where the size of the wave is dependent on the magnitude of the apparent wind, the fetch or distance of wind wave interaction and the duration of interaction. The wave period, T, measured in seconds is the time taken for the wave to move across its wavelength, the spacing between wave peaks and is measured in meters. The peak period, T_p, is the period between the most energetic waves and was provided with the Athens dataset. Waves of different heights and periods combine to create the sea state [23]. The significant wave height, H_{m0}, is commonly used to estimate the apparent height of the waves and can be derived from the spectral moments of the wave in a time domain. Figure 19, illustrates these two sea state variables over time.

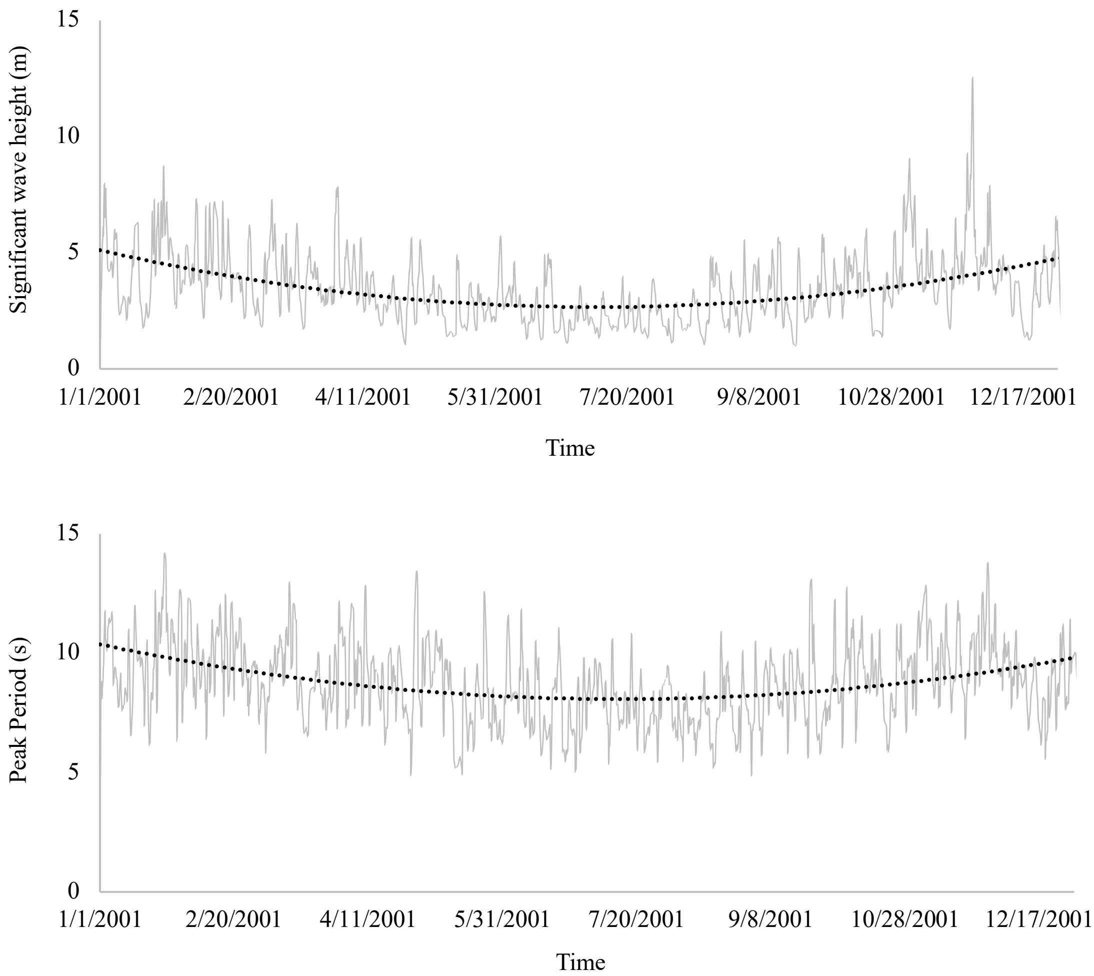


Figure 19. The hindcast model dataset from the University of Athens is demonstrated for resource bin 126_630 of the West Irish coast as presented in Figure 13. The peak wave period and significant wave height are represented as an example for a resource bin over the year 2001. A second order polynomial has been represented to demonstrate the decrease in both peak period and significant wave height over summer months.

Variability is apparent when considering the deviation of data across time, with the trends in higher wave highest and longer periods in winter declining over summer. The change in peaks further demonstrate the need to understand the power performance of a wave energy device and subsequent impact on grid infrastructure. The combination of the sea states over the hindcast data set are outlined in the occurrence scatter matrix, Table 2.

Table 2. Percentage sea state occurrence scatter matrix for resource bin 126_630

H_{m0} (m) \ T_p (s)	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	20
0.5	0.0	0.0	0.0	0.1	0.2	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.5	0.0	0.1	0.4	0.6	1.5	3.3	4.9	4.0	1.6	1.1	0.7	0.3	0.1	0.1	0.0	0.0	0.0
2.5	0.0	0.0	0.1	0.5	1.0	1.3	3.2	7.8	6.1	4.1	2.5	0.7	0.3	0.3	0.0	0.0	0.0
3.5	0.0	0.0	0.0	0.0	0.4	0.9	1.2	2.7	4.1	5.0	5.1	1.3	0.5	0.3	0.0	0.0	0.0
4.5	0.0	0.0	0.0	0.0	0.0	0.3	0.6	1.1	1.4	2.3	5.7	1.3	0.5	0.2	0.0	0.0	0.0
5.5	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.4	0.6	0.9	4.2	0.7	0.4	0.1	0.0	0.0	0.0
6.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.3	0.4	2.7	0.6	0.2	0.1	0.0	0.0	0.0
7.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	1.7	0.3	0.1	0.1	0.0	0.0	0.0
8.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	1.0	0.2	0.0	0.0	0.0	0.0	0.0
9.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.1	0.0	0.0	0.0	0.0	0.0
10.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.0	0.0	0.0
11.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0
12.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
13.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

The power available from the wave front is a function of these two factors and commonly expressed as a power, *kW,* per metre wave front. However, site conditions can influence the approximations used to derive power and are sensitive to the water depth. Deep water waves are classified by the ratio of:

$$h > \frac{\lambda}{2}$$

Equation 1

Where ratios between depth, h, and the mean wavelength, λ greater than 0.5 are considered to be deep water waves [23]. However, as presented in Table 2 there are occurrences where this is not true and another approximation would be more appropriate, including the shallow and intermediate depth wave approximations. To ensure that the correct wave power approximation is used, an assessment was made of the average depth at each resource bin location and the deep-water wave equation's suitability in terms of the percentage coverage of wave occurrences.

The resource bin method used in this work ensures that changes in bathymetry fall along the edges of bin areas and therefore the mean of the bin is representative of the average seabed profile. Across the study area the suitability for the deep water approximation has been compiled into Table 3.

Table 3. Percentage coverage of deep-water wave approximations for study area depths with minimum depth being 30m, device constrained, while depths above 200m capture all wave conditions.

Depth (m)	30	50	100	150	200
Coverage (%)	20	33	52	92	98

Although it is understood that area suitable coverage of the deep water estimation could be as low as 20%, the mean across the study area was found to be 71%. However, coverage increased to over 60-100% as, determined later in this thesis, over half of sites evaluated range between depths of over 100m to 200m. That said, it is known that applying this deep water approximation could have an impact on the results of the power. Therefore, the outcome of the wave power modelling is limited to this assumption.

Improvements to the modelling process for wave power estimations could be expanded as further work. This could be achieved by determining each cell locations depth and mean wavelength to satisfy the deep water ratio equation. Those cells classified as being in shallow water could use the appropriate wave power approximation. However, for the purposes of this work this assumption has been deemed acceptable and therefore, the following approximation for wave power was applied from [23].

$$Wave\ power\ (\frac{kW}{m}) = \frac{pg^2}{64\pi} {H_{m0}}^2\ T_e$$

Equation 2

This available power estimation is applied to each wave scatter matrix across all 52 resource bins as well as the mean annual 5km data points. Where water density, p, of sea water is assumed as 1,025 kg/m^3 and g, gravity and T_e, is the wave energy period and is defined from the wave spectrum moments in the following section.

4.3.3 Obtaining Energy Period

In practice ocean waves are not simplistic and contain variability. Therefore, an understanding of the random surfaces of the wave must be made using ocean wave spectra. The spectrum provides an insight into the distribution of wave energy among varying wave components. The wave energy period, T_e, is derived as a ratio of two spectral moments:

$$T_e = \frac{m_{-1}}{m_0}$$

Equation 3

However, spectral moments could not be obtained from the hindcast data. Therefore, a suitable spectral form needed to be assumed in order to evaluate the moments, m_{-1} and m_0. In order to determine the spectral moments from the hindcast data available, one form of wave energy spectrum was assumed for all the sites in this work. The Bretschneider spectral shape is typically used to determine fully developed sea states, such as those found off the western coastline of the study area, the Atlantic, with an unimpeded fetch.

This assumption to use one spectral shape could have an impact on final power production owing to the fact that other spectrum types might be a better representation. To reduce this assumption's impact, future modelling work could be conducted to identify the correct spectral shape for those sites in partially developed seas or with different criteria. For example, in sites with a limited fetch or partially developed sea, the application of the JONAWAP spectra could considered more appropriate. However, this work has derived the spectral moments assuming a Bretschneider spectral shape utilising the following definitions obtained from [111]:

$$m_{-1} = \frac{\sqrt{2\pi A}}{16\Gamma(\frac{3}{4})B^{5/4}}$$

Equation 4

$$m_0 = \frac{A}{4B}$$

Equation 5

Where A and B are the spectral constants relative to the mean sea frequency, f_m, and significant wave height, H_{m0}, obtained from the hindcast data and are estimated from [111] as:

$$A = 0.1107 H_{mo}^2 f_m^4 \qquad B = 0.4427 f_m^4$$

Equation 6

4.3.4 Wind Resource Estimation

The single resource parameter used to define wind energy production in this thesis is set as the wind speed. For the hindcast data provided by the University of Athens, wind speed is measured at an elevation of 10m. While a mean wind speed at each 5km cell point at 100m height above sea level was pre-determined from the dataset provided. As was seen in the wave data the temporal variation across the wind data, Figure 20 is apparent.

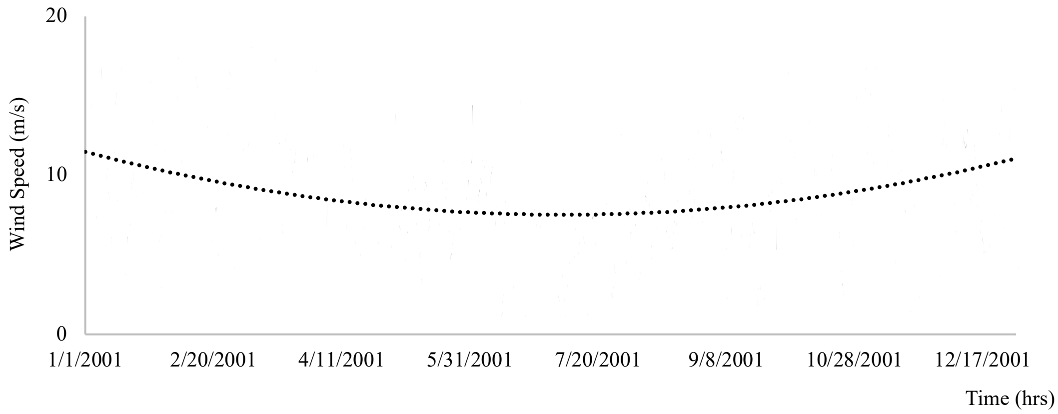


Figure 20. The hindcast model dataset from the University of Athens is demonstrated for resource bin 126_630 of the West Irish coast as presented in Figure 13. The wind speed is represented as an example for a resource bin over the year 2001. A second order polynomial has been represented to demonstrate the decrease in wind speed magnitude over summer months.

The distribution of wind speeds was recorded over each of the resource bins and is measured in time bins of 0.5s. The results of the occurrences are represented in Figure 21 for all of the resource bin locations.

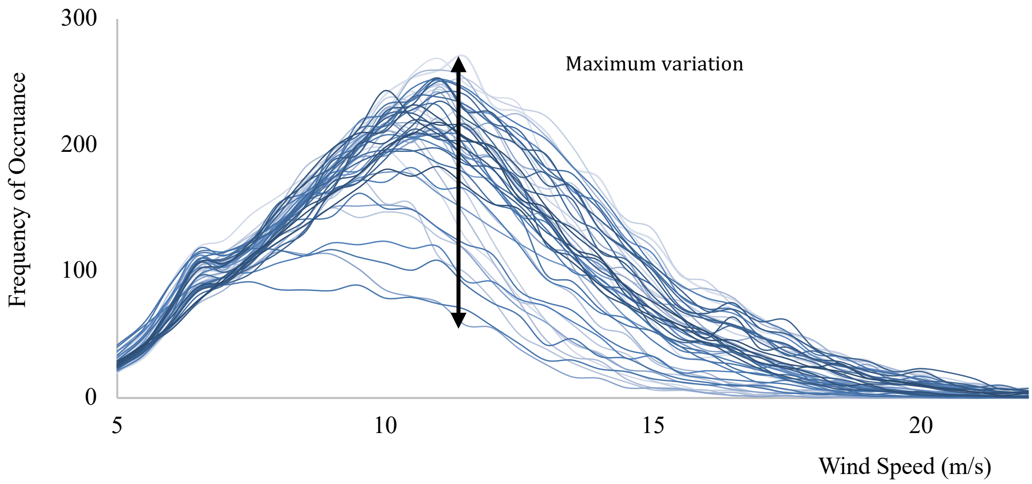


Figure 21. Wind speed annual frequency distribution for all 52 of the resource bins in the study area. Variation is demonstrated to be maximum between 10-15m/s.

As expected, the highest frequency wind speed bin is centred on the mean of approximately 12m/s. The magnitude change is also evident with extreme highs and lows in frequency being apparent. A range of 200hrs was observed as the maximum variation in wind speed occurrences. Therefore, it can be assumed that like the wave energy resource suitability wind sites will be highly location dependant.

The significance of local surface interaction of wind measured is known to have an impact on wind speed profiles and therefore must be accounted for. While surface roughness varies significantly with the surface type above the wind boundary layer frictionless movement is assumed [87]. The flow impedance created by surface interactions is known as the logarithmic wind profile power law which estimates the change between wind speed at the hub, U_{hub}, and the measurement wind speed, U_{Record}. The law describes the decrease over elevation between hub height, h_{hub}, and the recorded height, h_{record}, as a factor of roughness coefficient, Z_0, defined as:

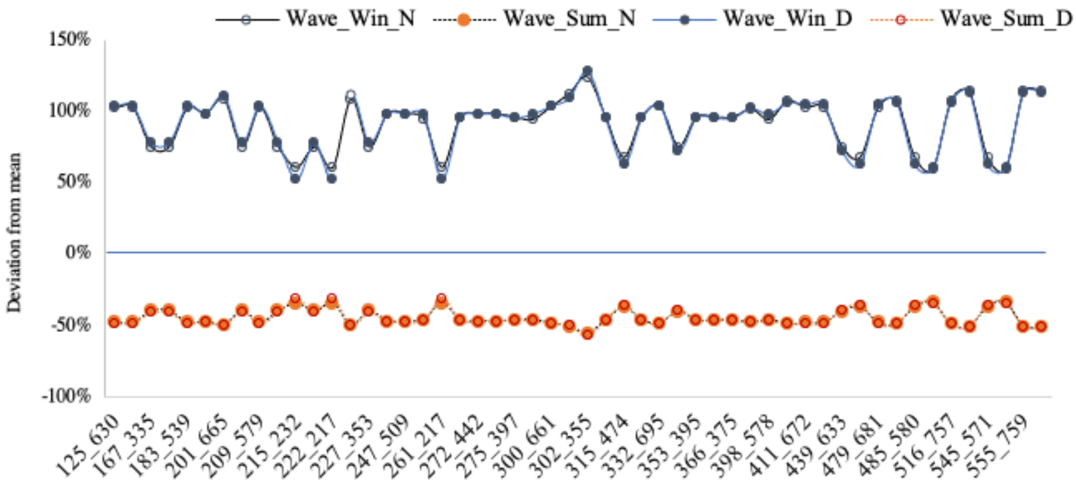
$$\frac{U_{hub}}{U_{record}} = \frac{\ln\,(h_{hub}/Z_{0)}}{\ln\,(h_{record}/Z_{0)}}$$

Equation 7

The factor of roughness coefficient is significantly lower over water than over urban structures or tall forest [112] owing to the reduced drag and interference. For this work a typical roughness value, Z_0, of 0.01m was chosen, representing open seas with waves [112]. While the sea state variability could impact drag and roughness it falls beyond the scope of work to explore the impacts of this phenomena. However, this assumption could be improved on via further work which could be conducted to establish a series of roughness values for the mean sea states found in each cell across the study area.

4.3.5 Temporal Variation

The significance of location based temporal analysis was made clear in the demand patterns observed in Figure 6. However, temporal variation is also apparent in seasonally sensitive energy sources such as wave and wind energy. Understanding the variability is important in relation to variable demand patterns. The seasonal time frames of summer and winter are measured from the 3 seasonal months of June - August and December - February. Whereas the diurnal time frames are measured over 6 hour time periods for day and night at 3-9 pm and 12-6 am. Figure 22 demonstrates the variability observed across the resource bin locations.



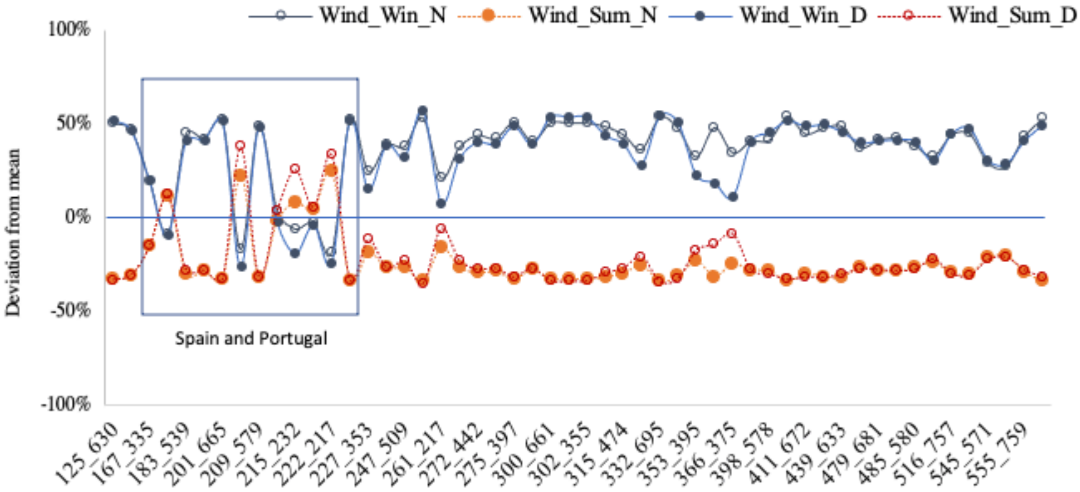


Figure 22. Wave power, kW/m (top) and wind speed, m/s (bottom) deviation from mean, across the four time frames of winter, summer, day and night. Inverse relationships of the wind model have been identified (boxed) in bins located of the coasts of Spain and Portugal.

The reference site 126_630, off the western coast of Ireland demonstrates the typical pattern to be expected of increased magnitude in summer and slight variations in diurnal time frames, with daytime summer resources being higher. Comparing the two resource types the variability in location is reduced in wave although the deviation from the mean is greater at an average of two times in winter and 0.5 times in summer. While wind relationships are less in mean deviation at approximately a mean of 1.3 and 0.7 for winter and summer respectively. However, several instances were observed where the typical pattern is reversed. Instances in both curves, but most pronounced in the wind case where all observed in the same location of the south coast of Portugal or Northern Spain. In these cases, the ranges are mixed with five locations recording summer resources are greater than winter. Further the variations in diurnal resource is also greater. This is significant when considering the demand patterns observed in Figure 6. This magnitude variation across seasons was also represented in [113] who observed the trends for the region between 1961–2014. The areas of significance matched the trend observed with increases in summer and decreases in winter.

4.4 Converter Performance

4.4.1 Wind Device Performance Characteristics

The wind turbine generation efficiency values used are more defined as the technology is more established and the device assumed in this work is assumed to be similar to existing wind devices and therefore a performance curve, Figure 23, for the 8MW device was estimated from the work in [99]. This power curve demonstrates the extracted power over wind speeds.

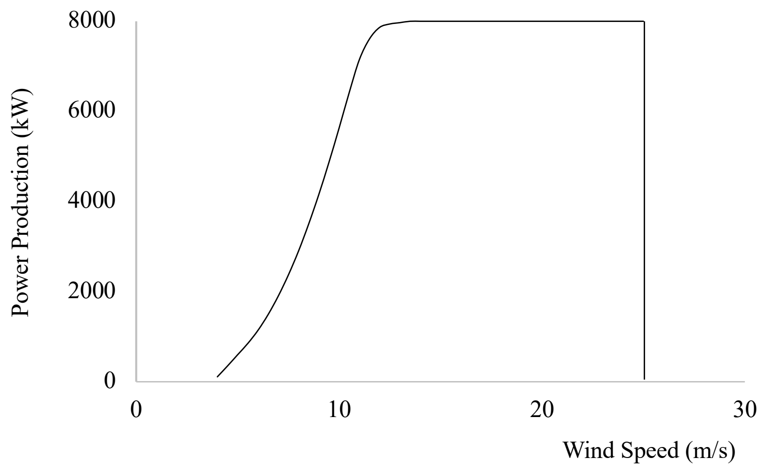


Figure 23. Reference 8MW wind device power curve demonstrating the cut in at 4m/s and ramp up of power until reaching optimal speed for operating before cut out at 25m/s [99].

The 'cut in' or wind speed where the device begins to generate power for the assumed devices is set a 4 m/s. While the 'cut out' speed, the extreme high limit where the device stops operation to avoid damage, set at 25m/s. The representation in the figure above with the power curve and cut off limit is a typical shape seen across offshore wind devices.

4.4.2 Wave Device Performance Characteristics

As wave energy devices extract power from a combined sea state they can have varying degrees of power generation efficiency. Establishing a generic efficiency across technologies and locations is inherently problematic. Not only due to the paradoxical issue of location-based resource characteristics driving generation performance, but also the bivariate nature of wave devices and technology divergence. However, for the wave technology the method of establishing efficiencies from non-dimensional parameters as demonstrated in [114] was applied. Using resource data for a characteristic device width of 10m, a coefficient of absorption is estimated for each wave condition. Extrapolating this across each wave condition created the wave power matrix used in this work, Figure 24

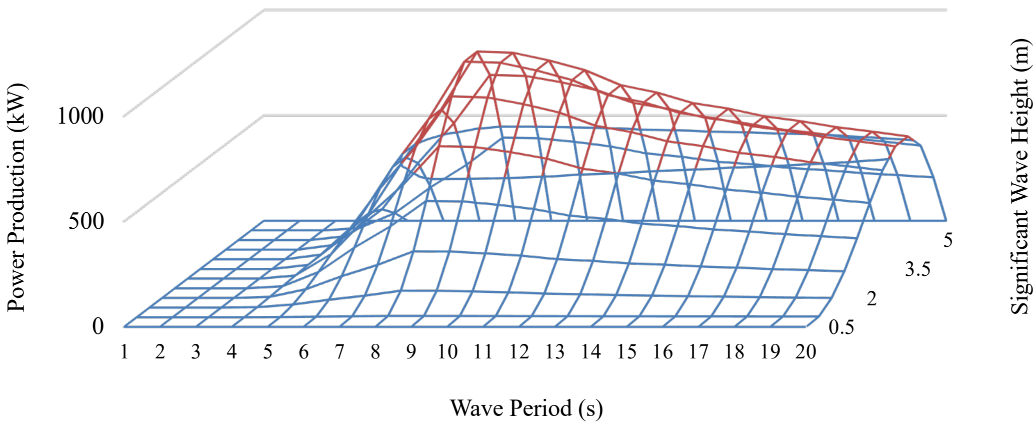


Figure 24. Reference 1MW wave device power matrix demonstrates the relationship between wave height, period and power production with the conditions of 8-10s and a wave height of 3.5m being most suitable for optimal power generation

4.4.3 Device Spacing

The device layout within the 2km cell matrix is represented in Figure 25. Convergence in technology and spacing requirements remain problematic as deployments are not as generic as conventional fixed systems. However, in deep water station keeping, multi-point moorings have been seen as most suitable in [109] [115] and therefore chosen for analysis.

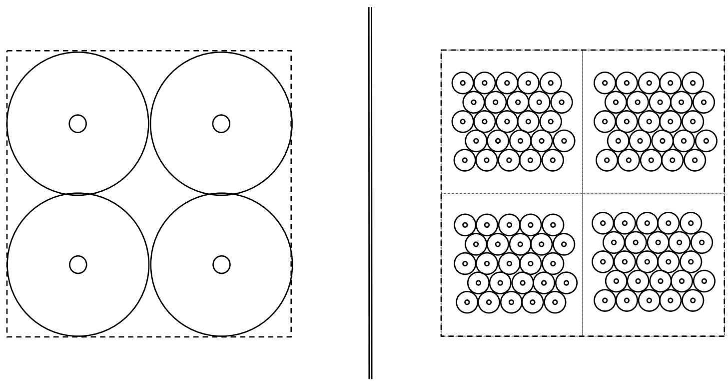


Figure 25. (left) wind cell spacing configurations assumed as approximately 8 rotor diameters [116], 1km Spacing. (right) wave point absorber spacing assumed as approximately 10 hull diameters [117] with a 0.5km corridor for operational considerations [118]. Leading to 4 wind turbines, 32MW or 100 wave converters, 100MW per 2km cell.

The cell spacing and layout chosen for the purpose of this analysis allows for 32MW of installed capacity for the wind devices and 100MW of installed capacity for wave devices. While the layout and configuration could impact the capacity in each cell this value was chosen as representative value only.

4.5 Device Power Estimation

After resource has been established for each of the hindcast bins the annual energy production associated with a device was estimated using a performance curve or matrix and the frequency of resource occurrence. However, due to the spatial course but temporal fine nature of the hindcast data two methods were applied to scale the energy production to the spatially fine 2km cells size used in this thesis. These include a scaling factor of resource datasets and spatial interpolation. Energy production obtained from each cell was approximated using the performance characteristics of the devices and an amalgamation of mean resource and hindcast data without losses.

4.5.1 Spatial Interpolation

To best represent the coarse resource bin data to the finer 2km resolution, an interpolation method was required. Wave climates and wind conditions are, as through the resource methods discussed, influenced by site characteristics. Locations in the near shore would not be suitable for such interpolation. However, as the sites proposed in this study are assumed to be at an average depth greater than 30m and distanced from coastal obstacles, it is assumed that a linear interpolation is suitable. Therefore, for each resource bin a spatially constrained Inverse Distance Weighing (IDW) analysis was performed in GIS. Similar processes and relationships where observed in [87]. The IDW analysis is a deterministic method for the spatial multivariate interpolation of scattered points and is based on the assumption that closer proximity is relative to similarity, as outlined below:

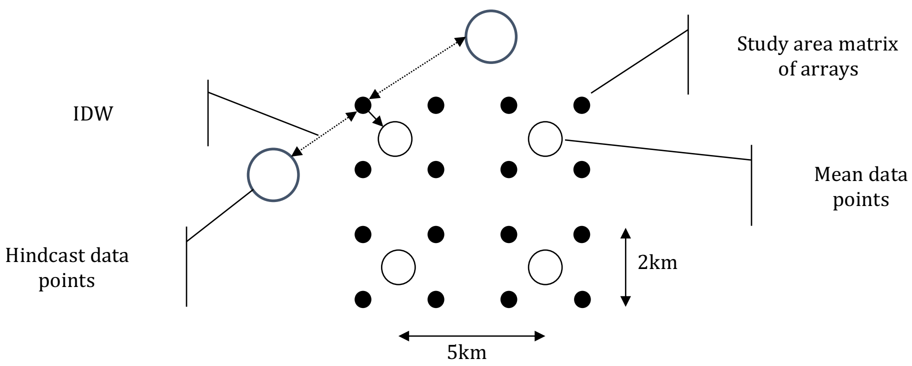


Figure 26. Spatial Interpolation of data from the hindcast points to the 2km cell matrix using an IDW process.

The IDW creates a raster layer for each variable which is used in the analysis. The process uses a variable search radius to depend on the relative distance to neighbouring points. Distance is raised using a mathematical power relationship. This value is sensitive as lower values determine a heavier weighting of local values yet minimal influence from other points. It was found that a power parameter of 3 was applied to favour local values yet allow for a wave and wind resource change greater than 5kW/m or 2m/s to occur over 100km.

4.5.2 Annual Energy Production

The spatial mapping and economic modelling work utilise the Annual Energy Production (AEP) in MWh. For both technologies the annual energy production was estimated as a function of the device performance and resource occurrence. The performance, power curve for wind or matrix for wave, was applied to each resource bin occurrence dataset to derive the sum of total annual power production over all occurrences and was evaluated as:

$$AEP = \text{Power matrix or curve} * \text{Occurance Scatter}$$

Equation 8

AEP provides power relative to the location of each resource bin, of which the hindcast occurrence data was available. However, in order to obtain AEP for the finer 5km resource matrix a scaling factor was applied to correct AEP to represent the increased granularity. The study area cell matrix uses a localised mean of the closest 5km resource points. In order to relate the power available from the 52 resource bins, the scaling factor was estimated as:

$$Scaling\ factor = \frac{\text{IDW mean resrouce at hindcast bin}}{\text{Annual mean resource at 5km}}$$

Equation 9

The scaling factor is applied and gives corrected device AEP to the 5km matrix, this is expressed in terms of GWh as:

$$Corrected\ Device\ AEP\ (GWh) = \frac{Scaling\ factor * AEP}{1000}$$

Equation 10

4.5.3 Mean Energy Production

The Mean Energy Production (MEP) in MW is derived for both technologies for the four periods over seasonal and diurnal frames over the hindcast data. Commonly the two time frames chosen are over observed extreme minimal and maximum values in energy demand as seen over day and night and winter and summer. Wave power and Wind speed were binned for the four time frames in each resource bin. Using seasonal mean values extracted from the dataset a scaled power ratio was derived similar to process above. This provided a ratio to be applied in obtaining the temporal mean energy production (MEP) extracted by either technology, defined as:

$$MEP = \left(\frac{\sum Device\ Power\ Out}{8760}\right) * \ Scaling\ factor$$ [8760 = hrs in a year]

Equation 11

4.6 Array Performance Estimation

The power estimated for the single devices is the representation of a pure generation system with no losses. However, there are several types of performance loss that can be attributed to the total energy produced by an array of 4 wind and 100 wave devices per cell. The practical losses that are assessed are, electrical, availability and wake interaction. It was assumed that directional losses are minimal due to the technical characteristics of the devices in question [87]. The wind turbine is able to turn into the wind while the heaving point absorber is able to capture multiple degrees of motion. The wave energy converter being a point absorber can extract power from multiple degrees of freedom and therefore do not require a prevailing direction. Similar is assumed for wind turbines as the hub and blades can yaw into a facing position.

4.6.1 Electrical

Systems used in the transmission of energy generated at the turbine to a collection point, offshore substation, contain certain losses. Transformers and interconnections losses can be estimated from past studies, observations of pilot projects and commercial scale projects of traditional offshore wind. Losses increase as the complexity, length of inter device cable and size of the farm increase [87]. While offshore energy system technology is being improved and the losses are heavily dependent on system design, an assumption was made with a mean loss for both wave and wind [119] [120]. An approximated 2% was assumed for the offshore floating wind sites. While it is assumed that the length of cable required to connect the larger number of wave devices is higher at 4%.

4.6.2 Availability

The availability factor is determined by the amount of time that the device can deliver the power over a given period. Availability, Figure 27, skews proportionate to the distance from shore as observed in [121]. Assumed staring availabilities due to failure are demonstrated as 0.95 for wind and 0.9 for wave energy technologies [34] [122] [123]. The range of availability values between device types was observed from the literature as discussed to be in the order 2-3%.

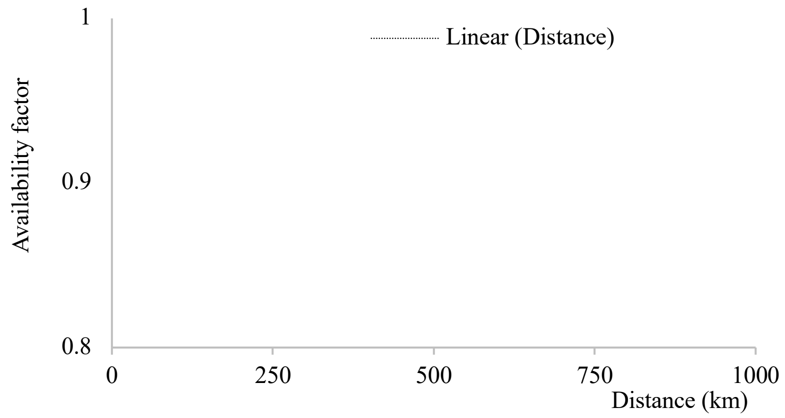


Figure 27. Representative availability relationship with increasing distance reducing availability.

4.6.3 Wake Interaction

It is understood that the extraction of power from a single device will have an impact on the neighbouring devices in the lee. This process is observed in wind farms as the disturbance to the air flow as seen in [124] and wave climate as measured in [117]. For both wave and wind energy the topic of optimal layout of devices remains contentious. Therefore, the optimal array layout and subsequent array performance of devices is an often difficult assessment to make at this level. Similar can be said for wind energy, although, with the comparatively uniform design and large-scale commercial adoption it has been established that array layout parameters are available. While it is beyond the scope of this thesis to incorporate an aero or hydro dynamic model to demonstrate the impact wakes might have on neighbouring devices a method to incorporate a resource reduction factor has been developed. The wave energy converter losses are assumed to be low, at 2% due to the spacing of the devices, similar was seen in [39]. The loss between wind turbines is considered to be higher however at 2% per cell of 4 devices. However, these values contain a degree of inaccuracy and could vary to 10% and 5% for wave and wind respectively.

A further wake loss is applied to sites after site selection in the final infrastructure model in section 7.6.3 as a factor impacting the output of arrays. The losses between large scale arrays is also a topic of consideration. While the extraction of one farm of wave or wind devices may be successful the location of a neighbouring farm may be affected. This has been hypothesised in field of wave energy and observed in the wind industry [116] [125]. For the purposes of this study a further wake assumption was made as observed in [96] [87] [126] where proximity to neighbouring farms increases the loss. Wakes are assumed to be at the worst under 10km for wind as observed in [125]. Similar losses effects are estimated with wave technologies due to wave power extracted by a farm resulting a reduction of 1.5-2m significant wave height. Waves are generated by unimpeded fetch and therefore an obstruction to his fetch will result in a loss in regeneration. A well-established principle in ocean wave dynamics, fetch length and wind speed relationship curves, also known as nanograms, can be used to determine the distance required for the associated significant wave height growth [127]. Therefore, a wave array wake effect is assumed to be up to 15km from site. These principles where then applied to the cell matrix power models as a spatial neighbour analysis. Any arrays in proximity lower than the wake limits act as a multiplier to the wake impact the reduction factor in the direction of the resource field. Directionality of the resource conditions was established from the hindcast data and is presented in 12.2.2

4.7 Energy Production Maps

4.7.1 Annual Energy Production Maps

AEP per cell was established for the use in the site selection models following. It is these data sets that will be used in the site suitability spatial modelling. The output of the energy production modelling for both wind and wave are presented in Figure 28.

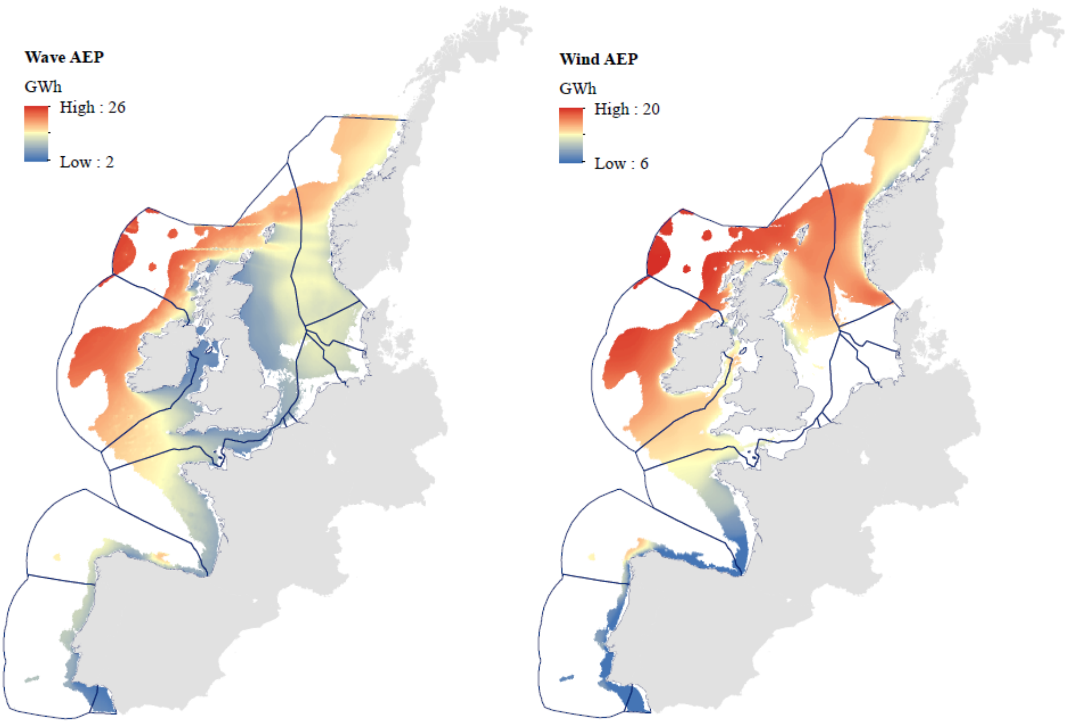


Figure 28. Annual energy production for wave (left) and wind (right) which have been clipped to the depth limitations as outlined. With a mean 12.5GWh and 17.5GWh AEP for wave and wind respectively.

Annual energy productions are, as presented, highly dependent on location. In the case of wave technology the influence of shadowing is apparent behind land masses, Ireland for example, where the energy production is visibly lower. This is less significant for wind but still occurs. While similarities across both technologies can be found in the location of extreme highs and lows. While comparing the two technologies across an annual time frame demonstrates that similar levels of production could be assumed. However, the efficiency, or capacity factor is variable between technologies due to their rated power over the cell area. Across the study area a mean wave energy capacity factor was estimated as 14% with a high top 90 percentile of 30%. A recent review [102] of wave technologies and their respective capacity factors for Western Europe and the Atlantic regions studied in this thesis at approximately 12% for point absorbers. While wind capacity factors are significantly higher with approximated mean values of 53% and highs of 63%. As discussed in section 1.2 fixed wind capacity factors for new developments are in the region of 45% [11]. Figure 28 also demonstrates the significance of power distribution across the study area with more focused productivity for wave in the north Atlantic. While similar hot spots are seen wind AEP is more evenly distributed with high production off northern Spain and the North Sea.

4.7.2 Temporal Mean Production

The seasonal and diurnal mean energy production levels are presented in Figure 29 for wave and Figure 30 for wind.

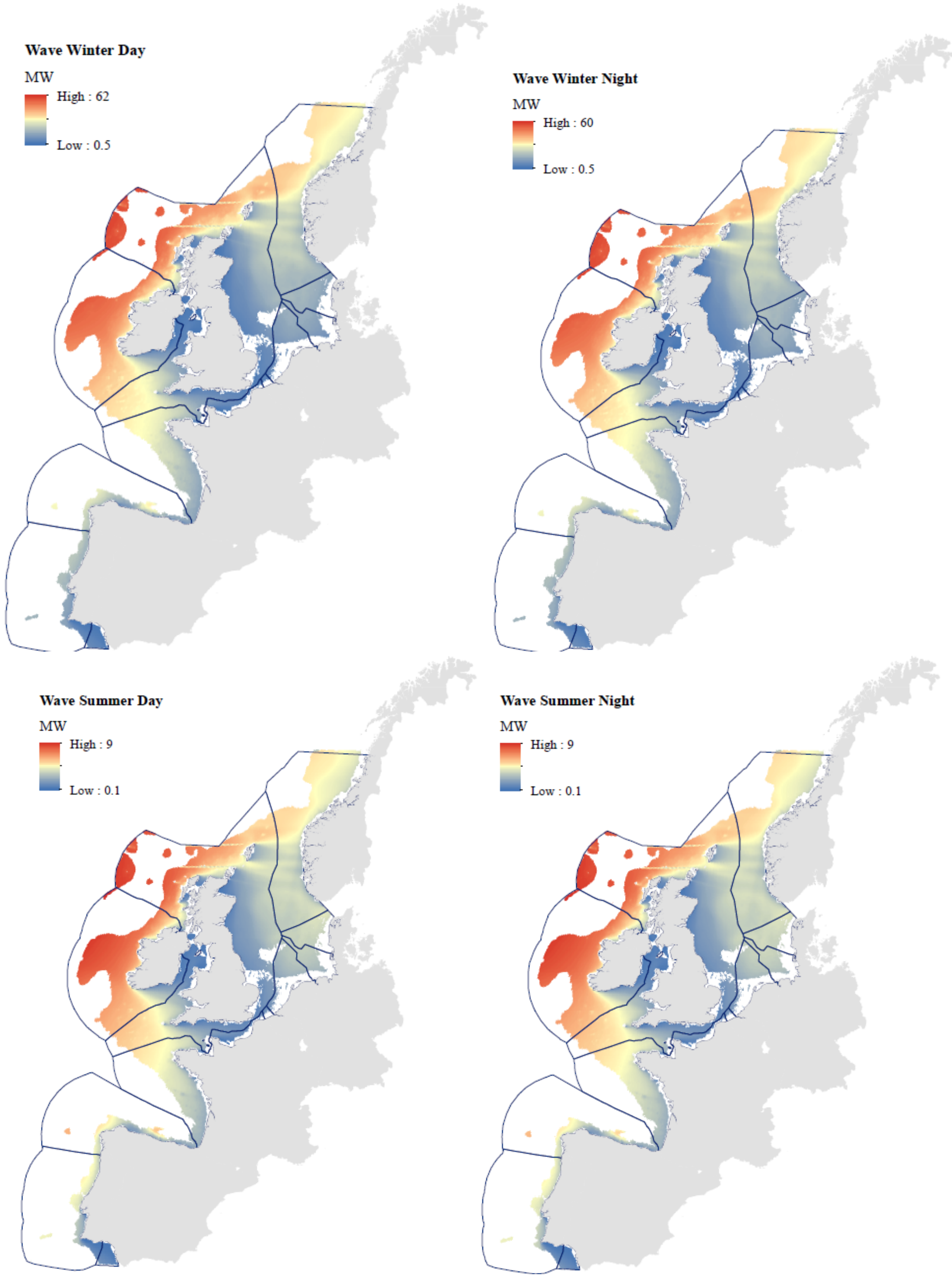


Figure 29. Temporal mean wave power outputs: 22 (winter day), 23 (winter night), 4 (summer day) and 4.5 (summer night). The plots representing differences between day and night demonstrate little to no variability in MEP magnitude. This indicates that the wave

power calculated is not as affected by changes in diurnal cycles or could be assumed to be minimal.

Wave power outputs between the time frames show spatially sensitive trends in power production. What is apparent is the large variation in mean power out between seasons with a mean recorded loss of approximately 80%. While the sensitivity of power production between night and day being minimal across the total study area. What is identifiable from the outputs is the variation is commonly assume trends that productivity is greater in winter. As discussed in section 4.3.5 a north south change was noticed between time frames, where Spain and Portuguese power outputs are greater in summer than winter. The mean capacity factor recorded between winter and summer are approximated as 23% and 4% respectively. This fluctuation in power output is to be expected due to the climatic conditions in the north and southern regions of the study zone. While similar spatial representations in power variability where observed the ocean wave energy study in [128] as well as the impact these variations have on wave device power output [129].

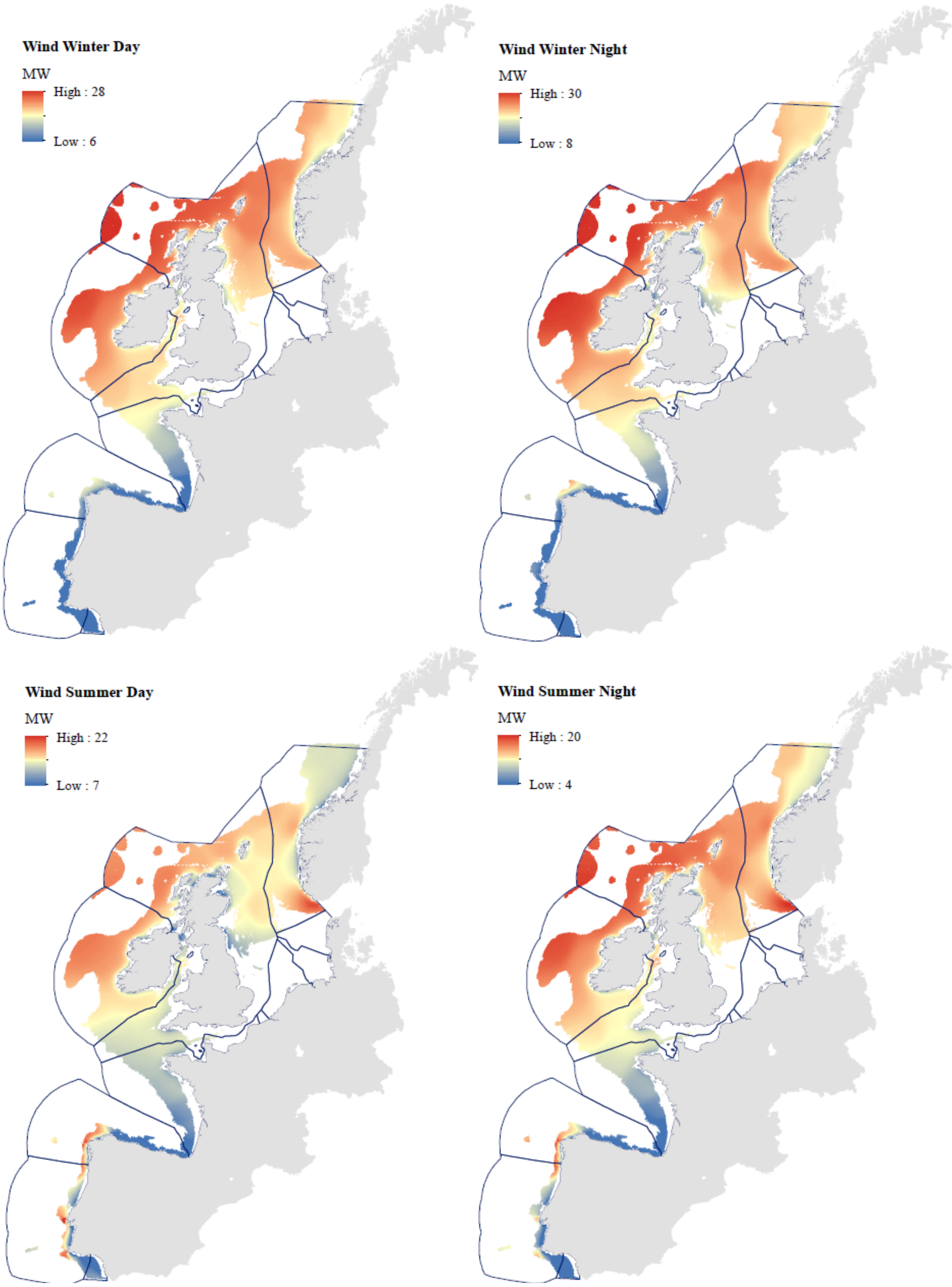


Figure 30. Wind mean temporal power outputs: 22.5 (winter day), 23 (winter night), 16 (summer day) and 15.8 (summer night). The plots representing differences between day and night demonstrate little to no variability in MEP magnitude except of the coast of Norway were magnitude increases at night. This indicates that the wind power calculated is more affected by changes in diurnal cycles than wave but is highly localised and change is minimal across the rest of the study area.

For floating wind the same power output magnitude variation between seasons. With similar north south reversals seen of the coast of Portugal and Spain. Less variability is seen however, between time frames with a seasonal, winter/summer, change of approximately 30%. Therefore, diurnal variation is more pronounced with visible increases between day and night in summer. This lower variability could determine that for the grid more floating wind power could be acceptable. The mean seasonal capacity factors for wind across winter and summer is approximated at 63% and 44% respectively. When considering that fixed offshore wind seasonal variation in Western Europe falls between 50% and 30% [11] a direct comparison of production viability can be made. Extreme highs in capacity factor in the top 90th percentile of the study area demonstrated a 78% capacity factor, which far out paces traditional wind installations.

4.8 Chapter Summary

The purpose of the preceding chapter was to represent resource at a spatial and temporal granularity most suitable to this type of work. Mean seasonal is known to be misrepresentative of actual conditions suitable for the technology type. Therefore, an attempt has been made to combine the operational suitability through applying performance characteristics to time series hindcast data. An industry representative wind power curve was applied. However, due to the lack of commercial development in the wave energy sector a theoretical bivariate wave power matrix was created. The performance of both devices was corrected against the mean resource data to provide more representative power production. This approach contains limitations due to the assumptions made into device characteristics and performance but have however been based on established practises. The spatial binning of hindcast resource points also contains a degree of uncertainty due to the area being represented. An attempt has been made to reduce this uncertainty with the application of an inverse distance weighting between granular 2km mean data points and the resource bins. After applying modelling techniques, a wave and wind energy production map was created for the study area. Initially this study created a technology unconstrained resource and power production map, however, after applying technology limitations the reduction martin zones is significant. The resource and subsequent power production is crucial in this study and dictates the suitability of sites and is a driving factor in LCOE modelling.

5. Site Suitability & Marine Planning

Abstract: Chapter 5 considers the geospatial process to form the first suitability analysis. Marine stakeholder conflict could arise with large scale array developments and established methods can be applied to floating WWE site suitability. The role of marine spatial planning is examined, and a novel method is applied to assess suitability of floating WWE.

5.1 Introduction

The background literature, 1.6.1, outlined a core issue with spatial planning and the sensitivities of site assessments for marine energy and other marine users. Those sites may have an impact onto other stakeholders, be that other marine industries, logistical, national authority or environmental. The variation between countries and their favourability to certain marine sectors, including offshore renewables, is also a factor when considering the geographical scope of this research. As was discussed in the literature review, these issues can significantly impact the assessment of site suitability and must therefore be addressed. In order to resolve the research gaps in marine spatial planning the following research question was proposed:

3. Considering other marine stakeholders where are the optimum sites from a marine spatial planning perspective?

As outlined in the overall modelling process for this work, Figure 10, the output of this chapter was to combine the previous models with the marine stakeholder assessments in a site suitability analysis. These layers were determined from the cell matrix and formed for each technology type for current and forecasted time frames. GIS software was used in this thesis to perform spatial analysis through the implementation of a multi criteria decision analysis. The process works through multiple layers to form a weighted linear combination (WLC) analysis and identifies relationships as outline in Figure 31.

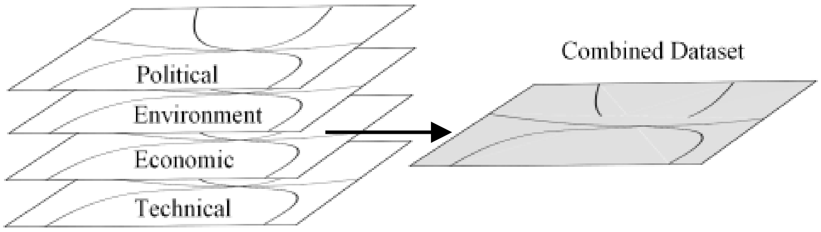


Figure 31. Multi Criteria Decision Making (MCDM) analysis demonstrating the combined layers constitution the multiple criteria being combined to for a single output.

5.2 Modelling Process

The modelling process, represented in Figure 32, outlines the tools and functions developed for the marine spatial planning stage. The process combined modules and performs weighted analysis to skew sites based on favourability to produce a site suitability map and an associated array cluster group.

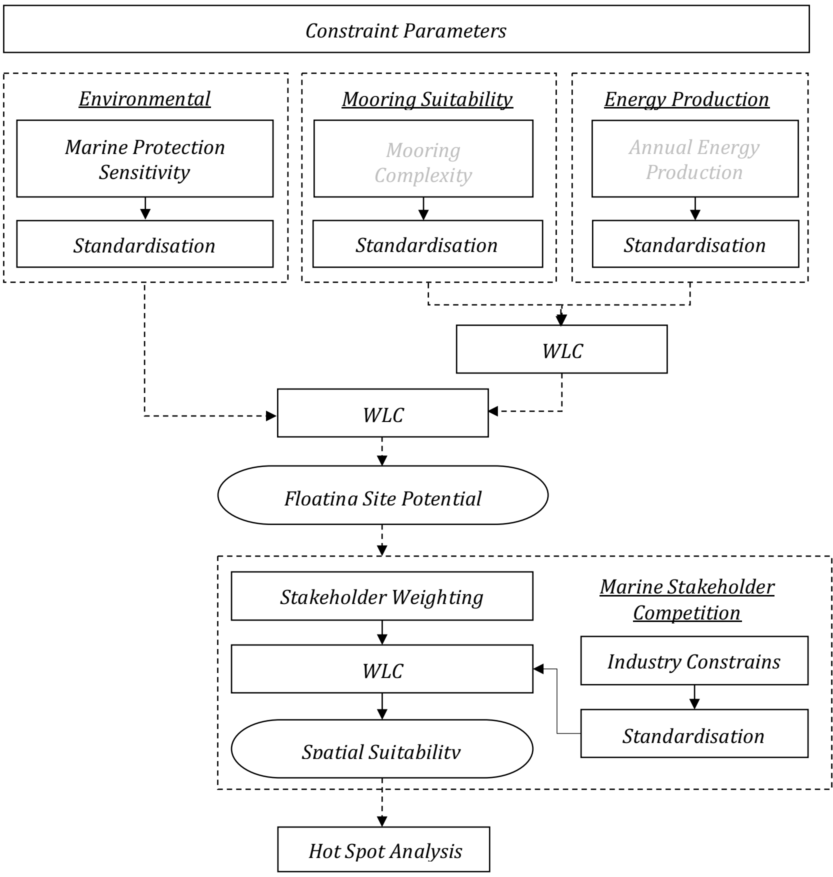


Figure 32. Flow chart of spatial analytical modelling processes with modules (dashed precondition boxes). Where the work of preceding chapters, energy production and mooring suitability are used as inputs but not discussed in this chapter.

The literature review into marine spatial planning techniques highlighted the process of fuzzy standardisation, 1.6.3. The process determined the transform of data sets to a scale of membership. The transform standardised the dataset to a 0–1 scale with the membership type dependant on the modelling outcome. Contrasting this, exclusion factors were assigned a Boolean value of 0 or 1 determining the area to be removed from the process. The level of integration or spatial overlap was accounted for at each restriction. Future deployment areas for established pre-existing offshore wind farms were used as validation to determine classifications made by industry.

A weighted combination was made between the mooring suitability, energy production outputs and was combined with an environmental module to determine the floating industry potential at each site. The marine stakeholder assessment assigns weights to the input criteria according to pre-determined industry values. The weightings were further skewed by the relative preference seen at each country. A sensitivity analysis iterated through multiple weightings between the marine stakeholders and wind industry values to give a range of suitability. Mean hot spot analysis established a relationship of variables relative to neighbouring features to provide a correlation value. A suitability index determined the suitable site score and the hot spot algorithm outlined the statistically significant grouping of cells. This process was established for each forecasted time frame of 2020, 2025, 2030. This was conducted to demonstrate the influence of marine users on the spatial distribution of sites with variable stakeholder factors, such as oil and gas licence zones.

5.3 Constraint Parameters

Aside from those areas already removed from the data due to depth there are several instances where developments would be prohibited from operating. As seen in past literature from EU maritime spatial planning frameworks parameters set in Table 4 were excluded. A radial buffer of 500m was included to all parameters in accordance with international maritime legislations for fixed structures [130]. A nautical exclusion of 3 nautical miles beyond coastlines was also applied. The stakeholders that are near shore have been excluded from the model automatically by the coastal buffer.

Table 4. Exclusion Data Types and Sources, while a full list of sources can be found in appendix 12.1.1.

Exclusion Type	Source
Sub Marine Cables	EMODnet (Cogea srl, 2015a)
Oil and Gas Installations	EMODnet (Cogea srl, 2015b)
Fixed Wind Farms in Operation or Development	EMODnet (Centro Tecnologico del Mar - Fundación CETMAR, 2016)
Marine regions	IHO (IHO, no date)
Marine Archelogy	EMODnet (MACHU project, 2016)
Shipping Density	ESA (ESA - CLS, 2009)
Vessel Tracks	MMO (UK GOV - MMO, 2014)

Datasets utilised were obtained in a polygon shapefile format and were therefore suitable for GIS analysis. However, shipping density required processing as it was obtained in a raster image format. Key marine navigational lanes and ferry routes were assessed with shipping density data and converted from raster to polygon layer format with density attributes maintained. Major navigational corridors of 90% traffic density have been removed from the model with a boundary of 6 nautical miles. This was established from MSP work conducted by the world ocean council [131] with such densities representing established shipping navigation corridors. Data with less than an annual density of 50% was set to 0 understood to be sporadic shipping and the remaining data, 50 – 90% was assessed for further analysis. This was converted into a polygon format with predetermined wind farms and other offshore structure further removed. The mean density removed was applied to the whole data set and shipping navigation lanes were identified. A similar approach to ship density track data and offshore wind farm location was observed in [132] and [133]. The area remaining for analysis after these datasets have been removed are represented in following figures for wind and wave respectively.

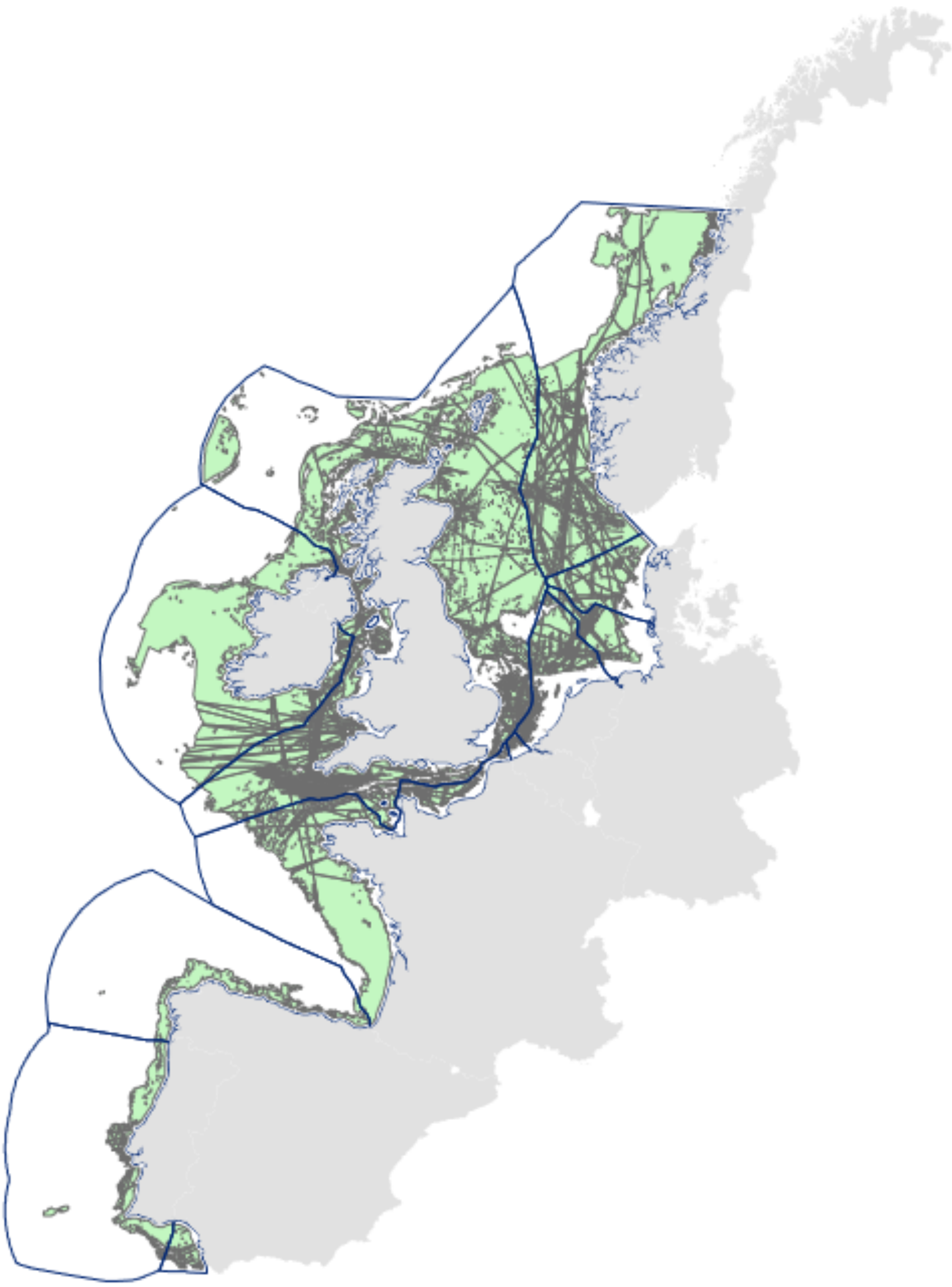


Figure 33. Wind Process area represents the shapefile remaining after the modelling constraints were removed for the wind technology. It was within this area that analysis takes place throughout the remainder of the thesis.

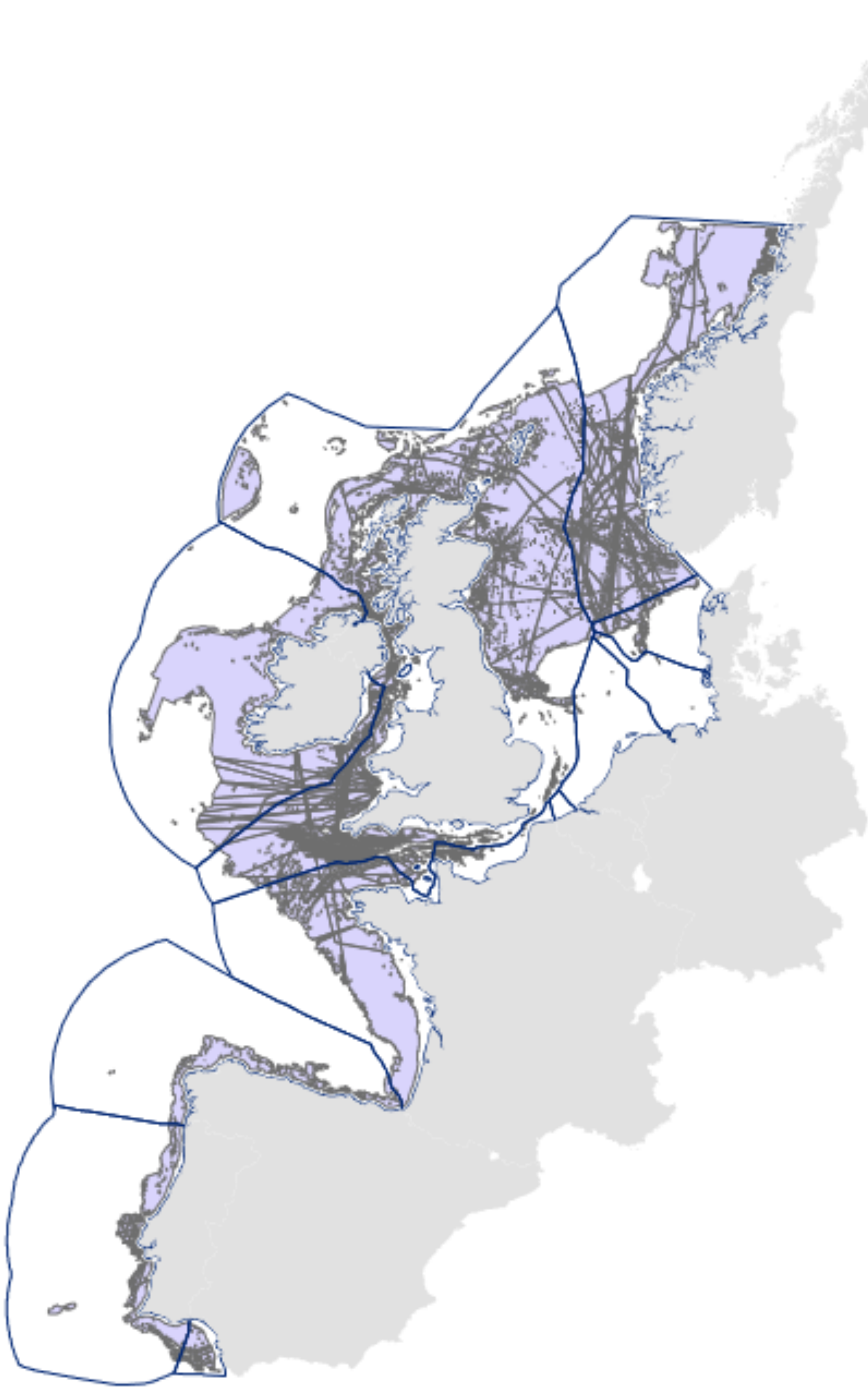


Figure 34. Wave Process area represents the shapefile remaining after the modelling constraints were removed for the wave technology. It was within this area that analysis takes place throughout the remainder of the thesis.

5.4 Floating Site Potential

Here value have been assigned to each of the inputs and are standardised accordingly to be used in the WLC functions. The output of which was the primary floating WWE potential used in the marine planning models in conjunction with models for other marine users.

5.4.1 Environmental Suitability

Marine protected areas were established from the Natura 2000 database [134] a spatial representation of this layer is presented in 12.4.1. Classifications were established as the relative impact on each receptor through identifying protective status, abundance, impact sensitivity and behaviour. Protective status being scored a 0-3 (None, National International). Abundance on a scale of, 0–2 (low to high). Sensitivity type to offshore operation, 0-1 (yes or no). The behaviour of species, 0-2, being classified as migratory or permanent. The impact of offshore wind turbines in arrays on bird habits has been contested and a commonly cited area of research. However, after extensive effort it was found that the impact is minimal at 0.1% collision risk among species, although nesting and migration confusion still remains [135]. Already planned and predetermined wind farms constructed, locations obtained from [136] were used to establish the areas to be totally removed. Table 5 demonstrates the remaining rankings of environmental sensitivity.

Table 5. Environmental suitability ranking ranging from 0-7. With ranks based on cumulative impacts based on Natura 2000 data.

Type	Ranking
Negligible	0
Sensitive	3
Present impact	4
Multiple impacts	7

5.4.2 Fuzzy Standardisation

The contributing layers were standardised through a linear fuzzy transform membership function as seen in Figure 35. The likelihood of set membership decreases as mooring and environmental make up rankings decrease and increase as annual energy production increases.

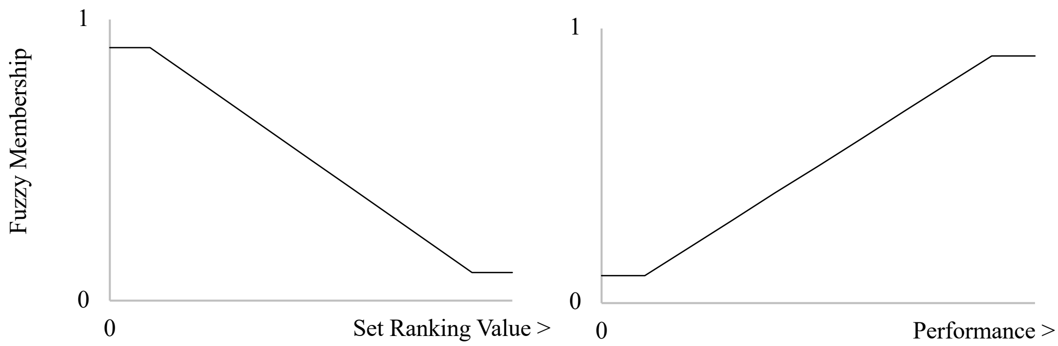


Figure 35. Left, decreasing linear fuzzy membership applied to environmental and mooring scores. Right, increasing membership function applied to Annual energy production.

Within the process the minimum and maximum crossing points between which standardisation occurs were defined and are excluded from the model being considered unusable for development. For mooring suitability, the site rank value was capped at 6 excluding those areas of extreme steep and geological value. Those areas of extreme multiple impacts have been excluded from the results as seen by the comparison of already planned wind farms and zonal segregation. Values over 5 have been removed from the analysis. The performance minimum value was used to define areas of extremely poor suitability. This value was set at a minimum annual energy production of 30GWh for wave and 40GWh for wind. These being a production value of less than half of the expected mean in the study zone. The resulting layers provide the most productive as well as the most technically and environmentally suitable sites for analysis.

5.4.3 Weighted Combination

Although it is understood that many factors play a role in the deployment of floating WWE. The strictly site-based parameters of performance, technical capability and environmental sensitivity are chosen as the purely site dependant characteristics. After reviewing the literature on MCDM and AHP it was found that little site-based similarity occurs across site parameter favourability. Therefore, a site development potential map was established purely from these three aspects through a weighted analysis as depicted in Figure 32. The process as described is comprised of two weighted linear combinations, the first being mooring suitability. This thesis has assumed a weighting favourability of 70% resource and 30% mooring score, seen in [51] [52] [53]. The combined model incorporates the environmental layer another variable and are assumed as evenly weighted as seen in [51]. This would yield sites with the possibility of highest membership values in each case. As with all the site parameters increased spending would change the technical ability and environmental sensitivity to overcome challenges. However, this thesis determined that the most 'probable' suitable site would be combination of all three fuzzy memberships.

5.4.4 Floating Site Potential

The preliminary results for the potential industry sites are represented in the following two figures for wind and wave respectively. The results are the weighted linear combinations of the site technical performance in respect with environmental site conditions.

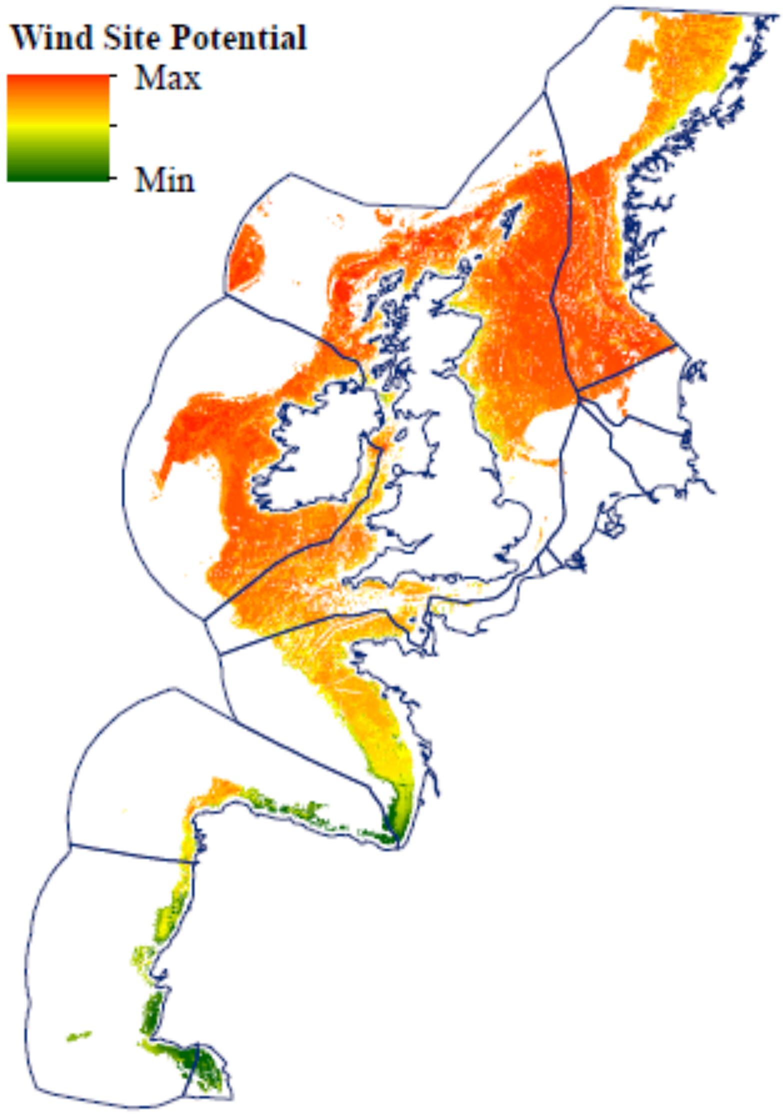


Figure 36. Site potential for respective marine study area for both Floating wind. Site potential regions visually more suitable in red shaded areas which predominantly are located away from the coast in more open marine space.

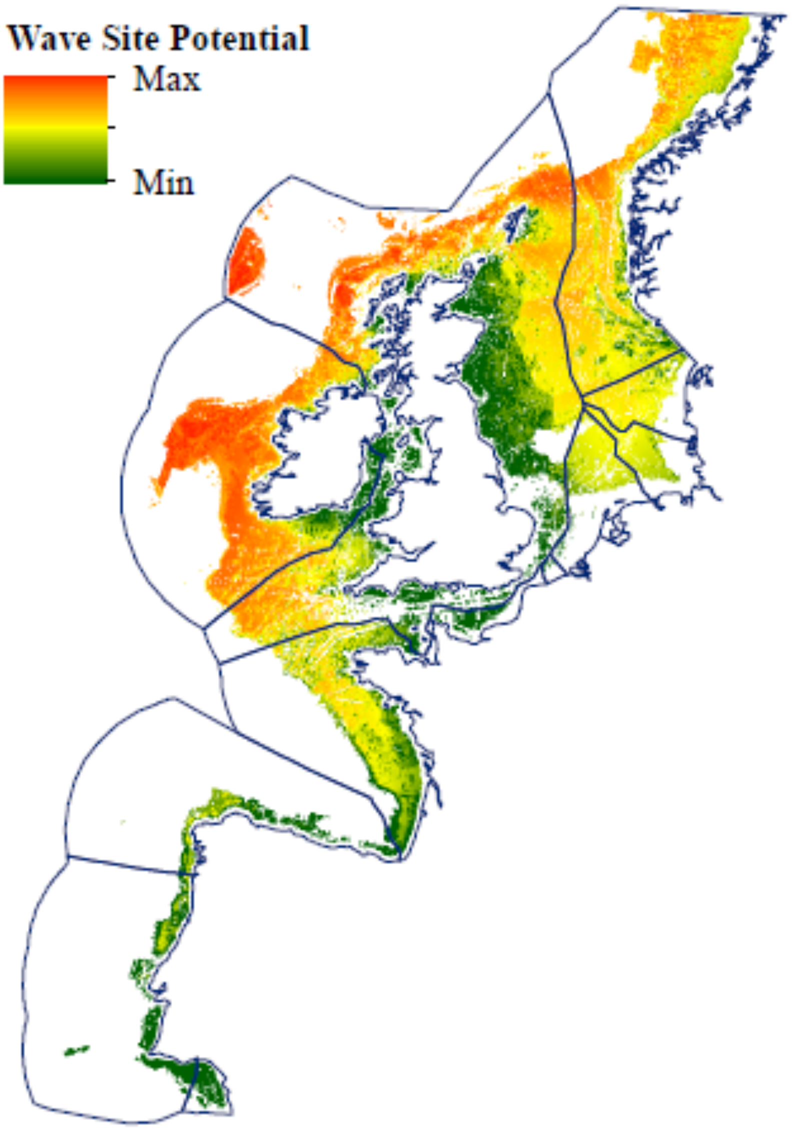


Figure 37. Site potential for respective marine study area for both Floating wave. Site potential regions visually more suitable in red shaded areas which predominantly are located away from the coast in more open marine space.

Between the two technologies variation in site potential is seen with approximately 70% of the area in the top 75% of suitability for wave and 30% for wave. It is therefore apparent when observing the two site maps that a larger wind potential was found in Europe. However, the wind potential was significantly more focussed. Impact of the excluded parameters and technology limitations are also observed. Most visible is the depth limitation and its significance to countries like, the Netherlands, Belgium, Denmark, Germany, Spain and Portugal. The latter two having comparatively lower potential in the remaining sea space than the UK, France, Ireland and Norway.

5.5 Marine Stakeholder Competition

This work splits the remaining stakeholders into two group. The first being, those that were to be excluded from the work through Boolean and fuzzy constraint limits. The second, addressed in terms of their industry valuation.

5.5.1 Restriction Constraints Ranking

The stakeholders from which commodity industries derived value were compiled from two methods, a spatial representation of these layers is presented in 12.4. This being established for fishing, hydrocarbon and aggregate extraction as a location and an activity metric. For oil and gas fields, obtained from [136], areas of high structure or pipeline density were excluded where fields within licence areas remained accessible. The licence areas have been scored based on the level of extraction and field size and the results classified and rasterised. Similar was established for marine aggregate extraction zones, data obtained from [137] where areas of frequent activity were scored highly. Scores for both extraction ranking are represented in appendix 12.4.2. Areas of operation with expiration dates, such as oil field licences were also factored in across the scenarios. Over time it was noticed that approximately 30% of the licensed fields and operational wells in the study zone where to re assessed of removed. This fluctuation into for time frames to 2030 has been included in the modelling. Fishing density data was obtained from the blue hub study [138] While comparing density data with wind farm deployments, clear boundaries were found and an approximate 80 – 100% density was seen to be an exclusion level. Catch data, over a 40 year period, was applied from [139] to create a metric of activity.

Table 6 . Marine stakeholder rank definition ranging from 0-3. With a 0 score recording no impact a 1-2 a partial impact and 3 highly impacting.

Constraint	Type	Ranking
Fishing	Density < 50%, active	0
	Density < 70%, potentially active	2
	Density < 80%, highly active	3
Oil and Gas	Licenced block, no activity	0
	Partial field development and licence	2
	Active field and extraction	3
Aggregate extraction	Licenced, no activity	0
	Licenced, potentially active	2
	Zoned, Highly active	3

5.5.2 Fuzzy Standardisation

In order to represent these layers in the model the significance of values had to be normalised with a weighting classification scale. All sets were applied to a decreasing linear transform, Figure 37 left, according to the ranked values established. Therefore, the likelihood of set membership included in the MCDM analysis decreased as the fuzzy membership decreased.

5.5.3 National Industry Valuation

Within the fisheries sector, assigning value to marine zones has often been carried out, as seen in [66] and [64]. In [67] catch weights were used to determine the gross value added GVA as a metric of industry importance. As seen in Each EEZ was given an industry valuation based on the% fleet catch of EU totals from data [139] and the industry GVA from the EU statistics hub and world bank databases. Although it is understood that catch levels and GVA values can rise and fall based on quotas and average was made from 2002 – 2017. The oil and gas (O & G) sector significance vary due to the distribution of resource. A sectoral GVA for each country was estimated from World Bank statistics [140]. However, the sector is inherently driven by the need for resources and susceptible to fluctuation. Marine aggregate mining operations have also been classified in a similar way using a volume of extraction, from Euro-Stat and proportional value in GDP. Energy targets have been used as a preference in weighting. The energy targets for 2030 were established from national commitment data [141], and forecasted projections [142]. The industry values for each country in GVA and energy commitment are normalised against the sum of all the study countries to provide a normalised national industry value. These values were then used to create spatial weightings through normalising all the industry values for each country to the sum. The results of the relative weightings are presented in, 12.4.2 where the dominance of some sectors over others can be observed.

5.5.4 Suitability Index

As discussed in this section, methods to define weighting relationships have been explored at length. However, this thesis aims to address the sensitivity of the marine stakeholders in relation to the new industry of floating WWE. Therefore, the aim of the analytical work in this chapter has been to associate cells in the study zone with a combined empirical value based on the degree of competition with stakeholders determined by the level of fuzzy membership. Furthermore, it has been assumed in this work that the development of large energy parks should not remove pre-existing stakeholder value but operate with minimal impact. This being due to potential protectionist policy restricting marine conflict or avoiding stakeholder value loss. The empirical value determined is classified as the Suitability Index (SI).

Index rating: The analytical method combined layers through the weighted combination approach determining an SI value. The application of an SI rating is a common GIS practice observed in spatial planning and the process combines the scores from the measured fuzzy datasets and considers each stakeholder ranking. The ranges for SI values were identified from the outputs of the fuzzy membership layered on top of inputs highlighting the following bins:

- SI (0.8-1) excellent, meaning no interaction was observed.
- SI (0.6-0.79) good, demonstrating an impact from a data layer was found with a low range of fuzzy magnitude.
- SI (0.4-0.59) average, impacts seen in one or more layers with an intermediate fuzzy magnitude.
- SI (0-0.39) poor, considered as too conflicting with multiple overlapping constraints with high range of fuzzy magnitude.

As this research considers the avoidance of multiple impacts with marine stakeholders, the exclusion of SI values below 0.4 were considered justified. However, such levels of exclusion are known to have an impact on the study area and is discussed in more detail in the results chapter in section 8.2.3. Preliminary SI outputs for both technologies have been represented in Figure 38 for current and forecasted variation in marine management due to industry changes.

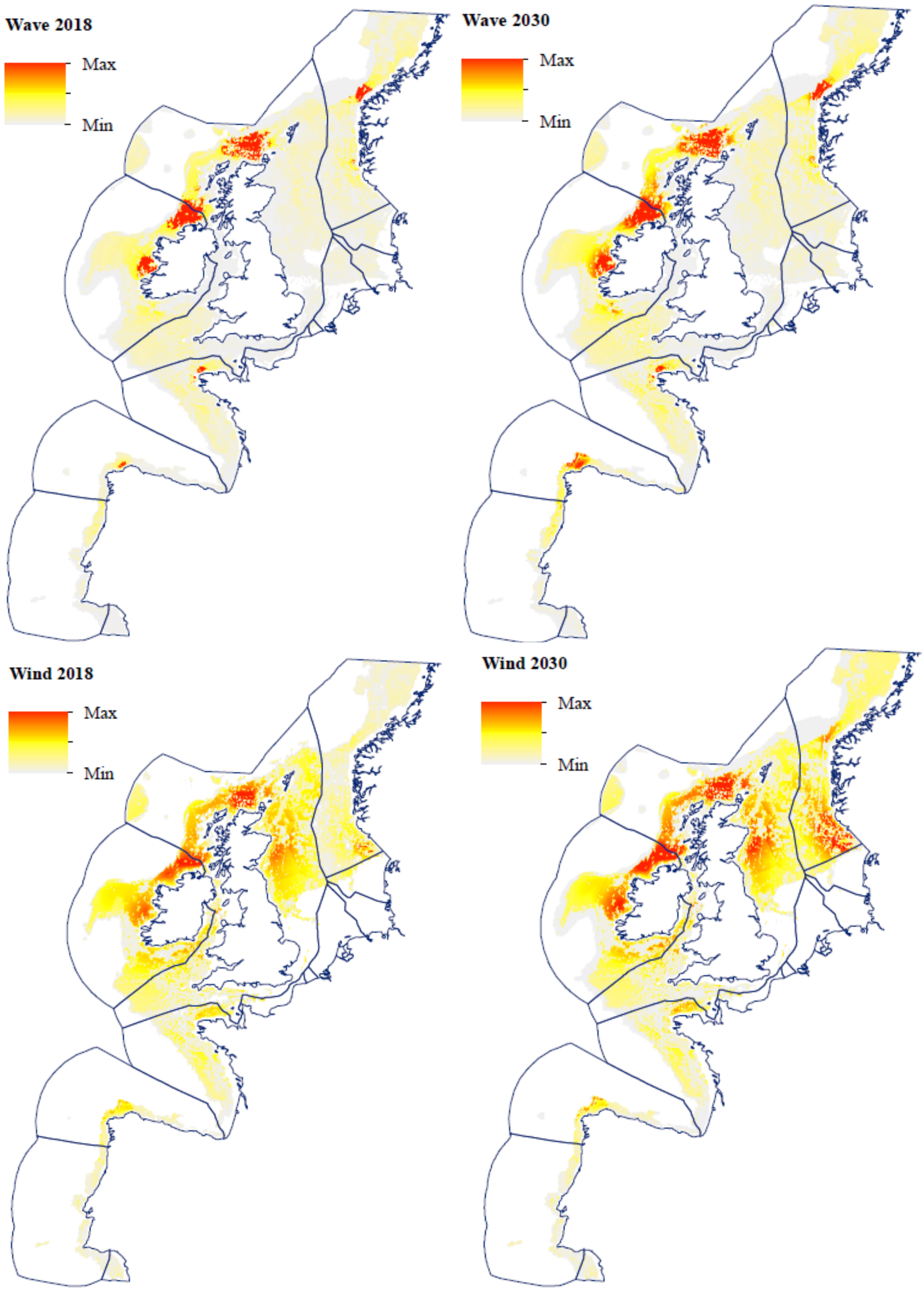


Figure 38. Floating wave (top) and wind (bottom) for all site potentials ranging from 0.4, the minimum accepted level of conflict with other stakeholders, to 1. Forecasts 2018 and 2030 have been chosen to represent the most significant variability over time.

The site suitability maps showed a similar distribution to the floating technical potential. However, that distribution was skewed by the relationship with other marine users. Considering wave energy technologies, there were 5 dominant locations for operation in 2018 around north Spain, north France, north and west coast of Ireland, Scotland and west Norway. Comparisons to 2030 demonstrated an increase in suitable area due to diminishing constriction of oil and gas fields. While the floating wind output demonstrates a wider market with hotspots being more frequent but less defined.

5.6 Weighting Sensitivity

Although a balanced approach was taken to the weighted linear analysis to demonstrate the impact of industry weighting sensitivity. A margin of 5% was applied to each variable for the balanced assessment. This value being chosen due to the mean variation addressed in value added to marine industries over time from the work in [61]. Focus of the marine policy case studies was aimed at separating the variables classified by policy and industry practise. By weighting variables and taking a total study zone mean, analysis could be made on the sensitivity of the stakeholders, displayed in Figure 39.

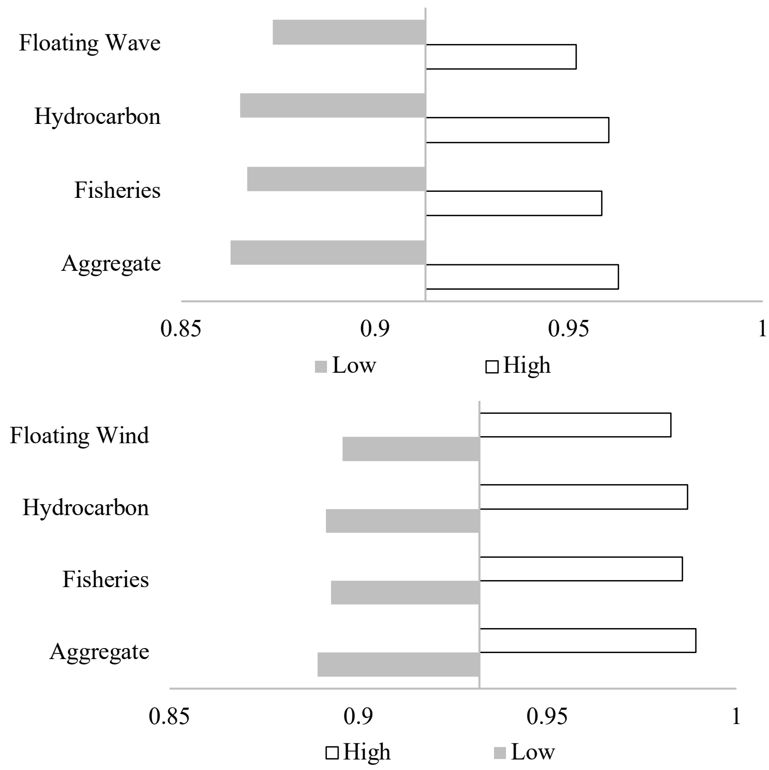


Figure 39. Sensitivity tornado plot: Mean of remaining area with an SI > 0.4 is simulated again with a 5% variation for each of the 4 component layers. The resulting plots demonstrated the sensitivity for wave (top) and wind (bottom) of each layer and the mean SI. Deviation demonstrates that a layer was more or less restrictive on the marine space. While

for wind increased levels of restriction where found with a positive 5% variation indicating that wind was more restricted than wave.

Between the two floating technologies the magnitude of spatial sensitivity was noticed to be greater in wave case. This was due to lower levels of area due to constraints imposed throughout the stakeholder competition mapping process. Between the variables a negligible change was observed with an extreme in suitability index score change of 0.8. Therefore, the results of the balanced weighting were considered suitable for analysis with an acceptable level of sensitivity.

5.7 Hot spot analysis

Identifying the location of clusters of cells which might be suitable for an array was determined by the statistic grouping model in GIS. The spatial weighted scores are extracted to the cell matrix with *SI* values of over 0.4. A GIS algorithm called the hot spot analysis is applied to locate the best groupings of good, 0.6 – 1, and excellent cells for development. The Getis-Ord, *Gi**, statistic hotspot algorithm in GIS measures the correlation between the cost and the associated suitability index score. The algorithm determined factors, a *Z* score and *P* value. The first being the significance of points being located near other high points in groupings and was measured in standard deviations. The second, *P* value, determines the probability of the grouping pattern observed or random. A High value, significant grouping of points and a low *P* value, best probability of true observation, were considered most favourable in the analysis. The result being a series of development zones of preference. The Getis statistic is expressed as:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - X \sum_{j=1}^{n} w_{i,j}}{s \sqrt{\frac{n \sum_{j=1}^{n} {w_{i,j}}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2}{n-1}}}$$

Equation 12

Where *Xj* is the attribute value of the cell, *wij* is the spatial weight between cells, *i* and *j* and *n* the total number of cells to be assessed providing the derivation of *x* and *s*:

$$\boldsymbol{X = \frac{\sum_{j=1}^{n} x_j}{n}}$$

Equation 13

$$\boldsymbol{S = \frac{\sqrt{\sum_{j=1}^{n} {x_j}^2}}{n} - (X)^2}$$

Equation 14

This process was iterated over each marine zone with a fixed distance neighbour band chosen to ensure groupings of a certain size. In this case the Euclidian value was set to 2km from each cell centroid or an approximated 6 in total cells. With the estimated annual energy yielding an approximate installed capacity of 500MW per group. The best scoring correlations were set as starting regions for development tranches for wave and wind energy. The highest performing hotspot value with a *Z* score greater than 0 and *P* value closest to 0 where chosen for analysis. An example output of the process is outlined in Figure 40 where one iteration has been performed for the UK marine zone.

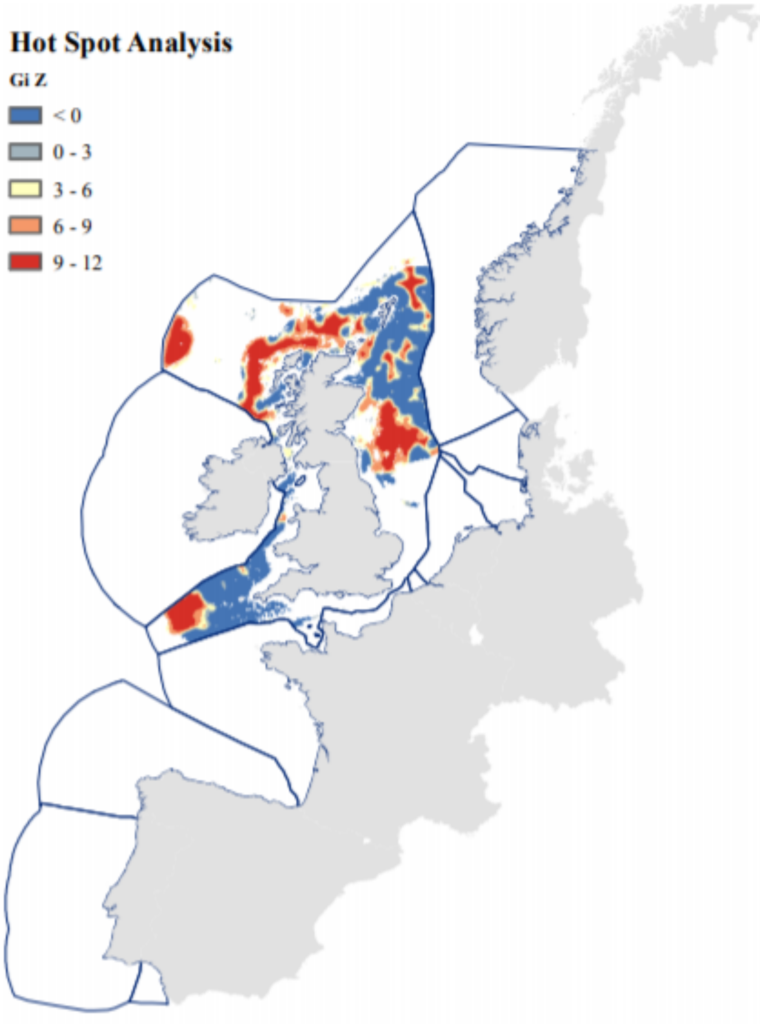


Figure 40. UK example of floating wind site clusters with statistically significant groupings of cells with an SI greater than 0.4 within 2km of one another.

The best performing zones were therefore ranked for the spatial suitable clustering of other cells. This grouping would form a prospective array for infrastructure and costing analysis. What is observed in this work is the grouping of four main hotspots for the UK, those being, the south west, east north east and North West of the country. These were determined to be the most likely to have a suitable sized grouping of high scoring cells.

5.8 Chapter Summary

This chapter set out to outline a novel process to not only remove those areas of the study zone that are unsuitable, but also determine how the floating WWE industry might best be developed with other marine stakeholders. Standard processes of, MCDM analysis, fuzzy standardisation and weighting linear combinations have been combined to reflect a range of suitability for the industry. Through applying a further technique of hot spot analysis, the grouping of highest clusters of suitable locations have been created for use in the following modelling work. However, the process of applying weightings in linear combination techniques leads to a degree of uncertainty. It was found that the margin of error was deemed minimal enough to apply the method. Therefore, the suitability maps are appropriate for the cases laid out in this thesis. The output of this section provided the first set of site potential data for use in the following cost and infrastructure assessments.

6. PROJECT COSTING

Abstract: After identifying sites of technical and marine management suitability the remaining area were assessed for their levelized cost of energy, LCOE, relative to infrastructure. The LCOE estimation method defined in this chapter was applied throughout the work and used to define site suitability with infrastructure.

6.1 Introduction

In order to develop a site of interest it must be considered economically feasible. This would require a site to have a competitive LCOE (levelized cost of energy). The cost of an energy system is typically defined as the total costs of fixed capital expenditure (CAPEX) and total variable operational costs (OPEX). While the levelized cost is relative to the energy produced over projects lifetime and is therefore defined as:

$$LCOE = \frac{(CAPEX + OPEX)}{Lifetime\ Energy\ production}$$

Equation 15

To define spatial suitability and LCOE, the relationship between the site location and project cost had to be examined. The core site-based cost components assumed in this thesis include installation, maintenance, grid connection and moorings. These factors are driven by the distance to infrastructure and the depth at site. As observed in the literature review many previous assessments into site suitability of offshore renewables utilising a GIS platform consider the distance to the coast or a fixed set of infrastructure locations. However, by comparing LCOE values for fixed locations and any coastal location the influence of infrastructure locations could be measured. Therefore, an assessment of proximity to fixed infrastructure locations would demonstrate the impact of distance on cost while proximity to any point on land might indicate the influence of designing infrastructure towards the industry. Therefore, the following research questions was applied:

4. Does existing port and grid infrastructure affect the selection of sites for exploitation?

6.2 Floating Wind and Wave LCOE

Due to a lack of project development history in the floating WWE industry it was problematic to estimate the cost of individual components. A mean was estimated across studies into varying site-based costs assessments to provide two reference cost case studies, Figure 41. These were utilised to determine the relative proportions that these factors have on the project LCOE, a similar approach was observed in [87].

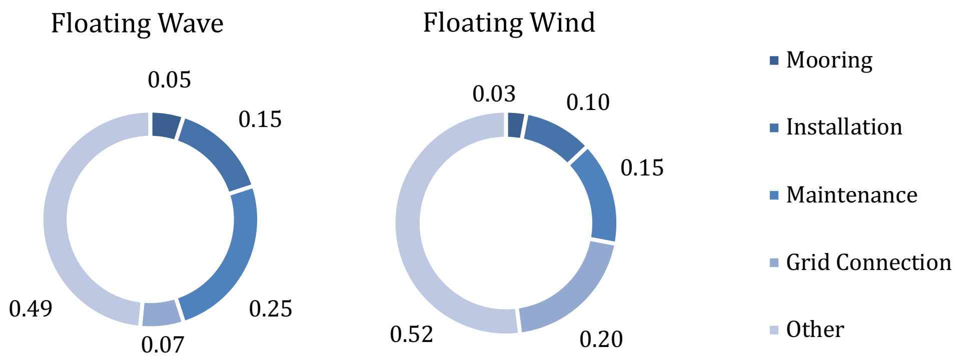


Figure 41. LCOE percentage breakdown. Site sensitive factors of mooring, installation, maintenance, grid connection are examined in detail. Other costs refer to project CAPEX of materials and converters which remain a fixed percentage.

Wind cost proportions were based on the project costs of 6MW turbines at a 20 year life span over a 500MW project in [34]. An assumed starting LCOE of £150/MWh was estimated from [34] and [35]. While wave values where assumed from [39] and [38] as a project at a 20 year life span over 100MW project at a starting cost of £300/MWh. While these two LCOE values seem considerably larger when compared to the LCOE values of other energy sources as seen in 1.4. A price of £100/MWh or less would be considered competitive relative to other renewable sources at this stage of development.

6.2.1 Site Driven Cost Variables

The method observed in [87] and addressed in [45] used site based factors to skew the proportional relationships of each component. The site variables that drive these factors are based around distance and depth. These have an influence on transit times for maintenance and installation crews, cable laying cost over distance and the depth of site for moorings. While not knowing the exact component costs for the project's cost curves for these variables were established. The cost curves, presented in Figure 42 and established from industry reports, demonstrate the site factor that will skew the project component cots.

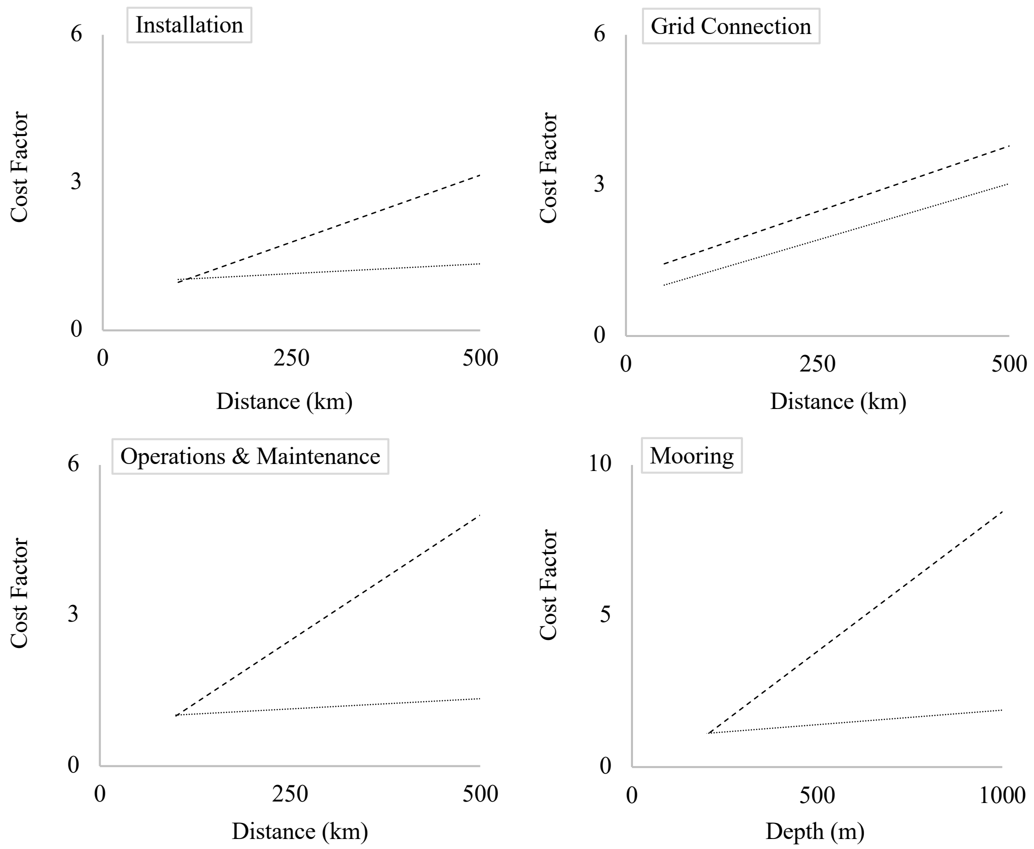


Figure 42. Dotted (wind) Dashed (wave) site dependant cost factor curves. Mooring and OM costs for wave devices have significantly steeper increases compared to wind due to the number of devices being installed in each cell. 100 wave devices against 4 wind turbines yields far greater volumes of mooring equipment and maintenance crews. Grid connection gradients are uniform as it was assumed similar process are observed for both technologies.

The floating wind curves were assumed from the study on component driven costs for distance to shore for installation and maintenance as well as mooring depth seen in [34]. The cable laying cost and distance to shoreline connection were established from offshore wind industry data in [143]. While being more established and being able to utilise the established fixed wind industry data, wave energy curves have been established from UK government study into the site driven parameters [144]. From reviewing the literature, it was found that some cost estimations are more variable than others. Operations & maintenance and installation costs being the most variable with a 10–15% deviation. While grid connectivity and mooring variability could be less variable at 5–10%.

6.2.2 Cost reduction

The rate of cost reductions was factored into each metric using data from the Carbon Trust's estimates of reduction over time [38]. It was known that overall learning improvements over time will affect LCOE. The thesis assumes that the industry was at a global level of deployment readiness and are not influenced by the deployments proposed. Therefore, it was assumed that at

2018 technology will not have progressed, but by 2030 costs will have come down. To account for this general learning rate over time an assumption of a cost reduction over time has been made, as represented in Figure 43.

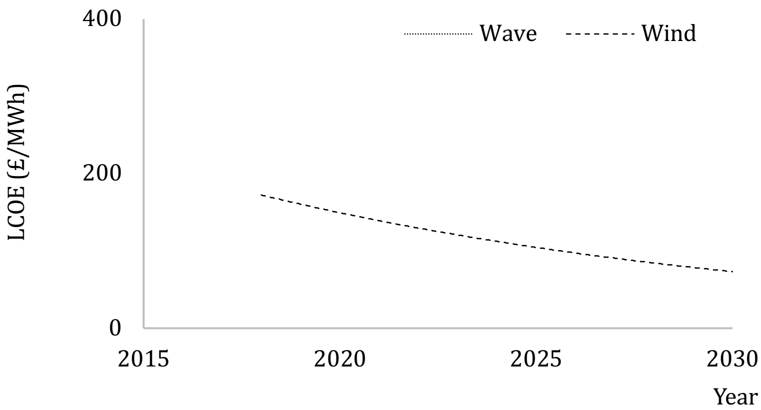


Figure 43. LCOE reduction curves overtime for wave [145] and wind [35].

Although based on established approximations this factor was known to impact on the overall feasibility for deployment and therefore a margin of error is accounted for as discussed in section 6.3.3. However, in terms of this analysis it does not impact the roll of location driven infrastructure suitability and therefore cross comparison using these reduction values were made. These assumptions include a level of variability as seen in the cost reduction literature for wave [145] and wind [35]. This variability could see a deviation of 25% and 15% for wave and wind respectively.

6.2.3 Cost Estimation

An assumed 20 year lifespan for the cost per cell was taken as an assumption in the LCOE owing to the industry estimates seen in [34]. Although this could be considered a conservative estimate as projects are now expected to be reaching approximately 25 year lifespans. Furthermore, the analysis was based on the established methods and data of the time and was intended for a representation of site suitability and not a direct forecast of exact costs. Applying the site determined factors with the proportional project percentage cost driver gives a derivation of:

$$LCOE = \frac{(I_c * R_I) + (OM_c * R_{OM}) + (M_c * R_M) + (G_c * R_G) + (Other\ Fixed\ Costs)}{Annual\ energy\ Production * 20\ yrs}$$

Equation 16

Where installation, I_c, operations & maintenance, OM_c, moorings, M_c, and grid connection, G_c, are relative the site sensitivity factors from the curves in Figure 42. The corresponding relative cost, R, for each variable is observed in Figure 41 and are obtained from literature. The relative value corresponds to each cost factor, for example R_I, refers to the scaled project cost for installation. This was conducted for each of the cost components. Within the GIS model the cost function was applied to each cell in the study area and for each potential time frame. Depth was attributed to each cell from the bathymetric data. In this work relationships between the location of infrastructure and lack of a fixed location was used to answer the research question. The cost model for each cell included a euclidian distance function that evaluates every cell's position relative to either the coast or infrastructure point. The two infrastructure datasets are demonstrated in the following figure.

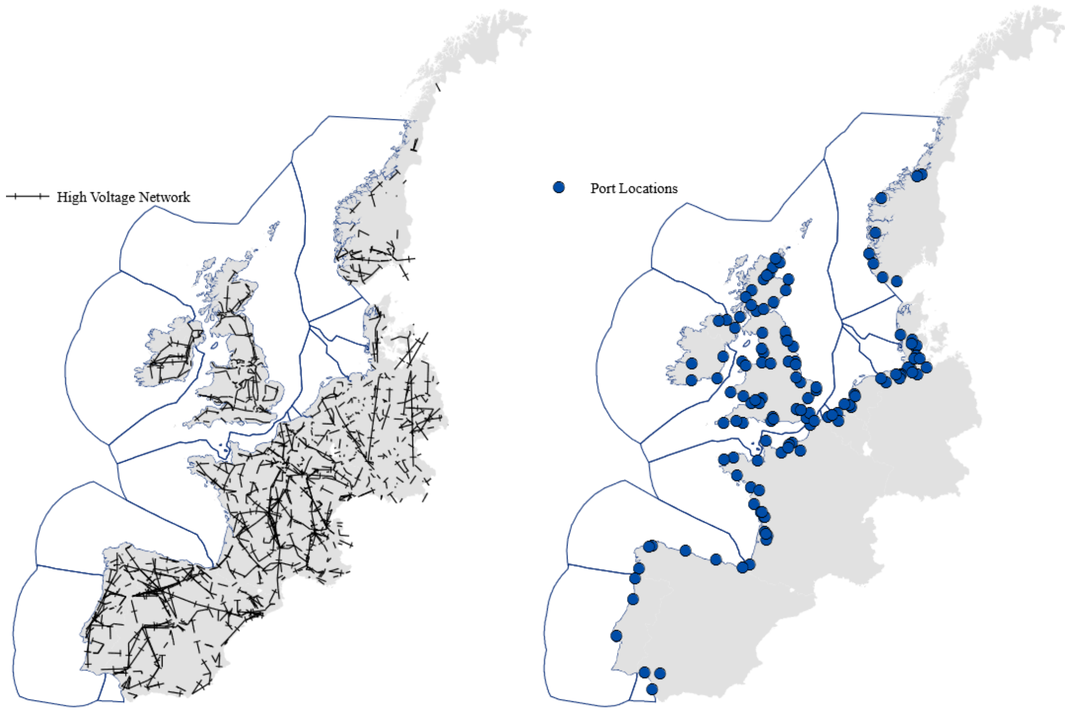


Figure 44. The European high voltage network (left) and existing port facilities (right) relative to the study area. Port location data was estimated from the suitable port identified for floating deployments evaluated in [146] . While grid locations are assumed to be anywhere on the high voltage system of Europe [147]. Where high voltage was assumed to be transmission lines over 100kV for large scale developments, as discussed in section 1.5 .

6.3 LCOE Analysis

Cost values were established for each cell across the study area for the case of the fixed infrastructure locations. The distance as well as other LCOE drivers can be assessed here for their influence across the cells. Although Annual Energy Production (AEP) was highly significant in site selection, due to the high variability in site conditions, it was not the only significant cost driver. Results showed that the cell values where not linearly comparable to performance. Figure 45 demonstrates the comparison of performance as AEP MWh against cost.

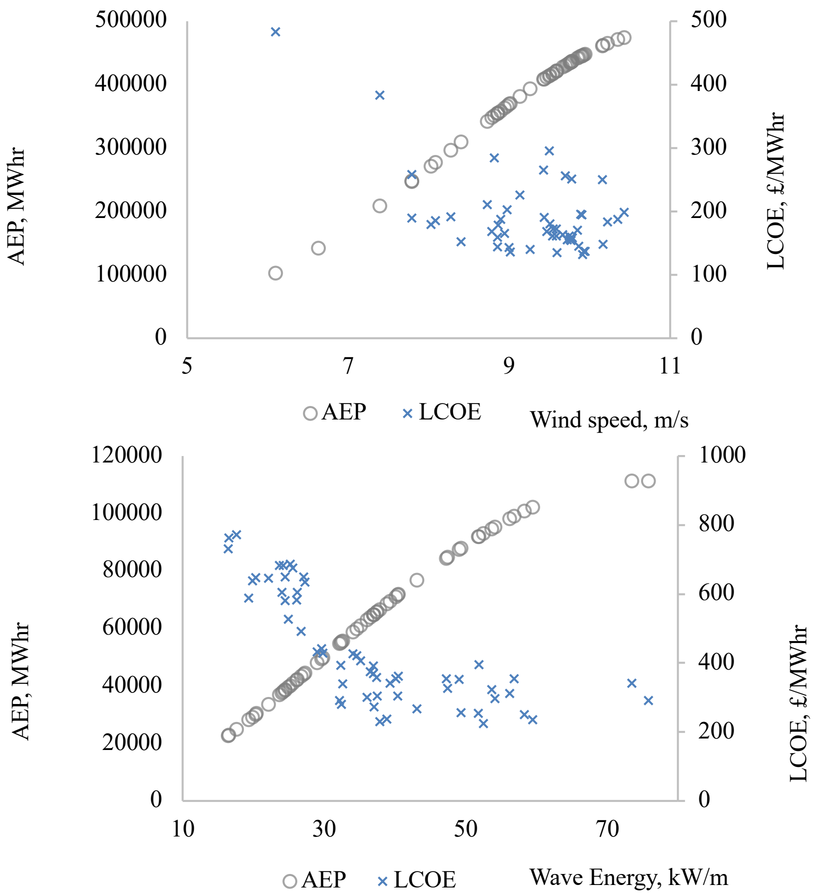


Figure 45. 2018 scenario data of cell performance of wave (top) and wind (bottom) over its relative resource characteristic against LCOE. With correlation coefficients of -0.79 (wave) and -0.56 (wind).

Distributions of operational ranges were observed when assessing the relationship between cost and performance in Figure 45. It can be seen that the majority of values fall within the ranges of frequent AEP occurrences. Further, the dispersion of LCOE highlights the impact of the other cost variables had on the overall LCOE. The scatter plots therefore show that, although a close correlation was seen between AEP and LCOE, other cost factors can be significant. Further understanding of these factors was explored in depth through the application of sensitivity analysis at the end of this chapter.

6.3.1 Cost Comparison

Cost values were extracted for the fixed infrastructure locations as demonstrated in Figure 44 and were described as infrastructure constrained LCOE's. While unconstrained LCOE's refers to the model using a Euclidian distance measure to any main land location. The unconstrained model representing the ideal scenario where infrastructure is perfectly suited to developments. Figure 46 demonstrates the potential capacity for floating wind and wave LCOE output with distance cost drivers either constrained or unconstrained by infrastructure.

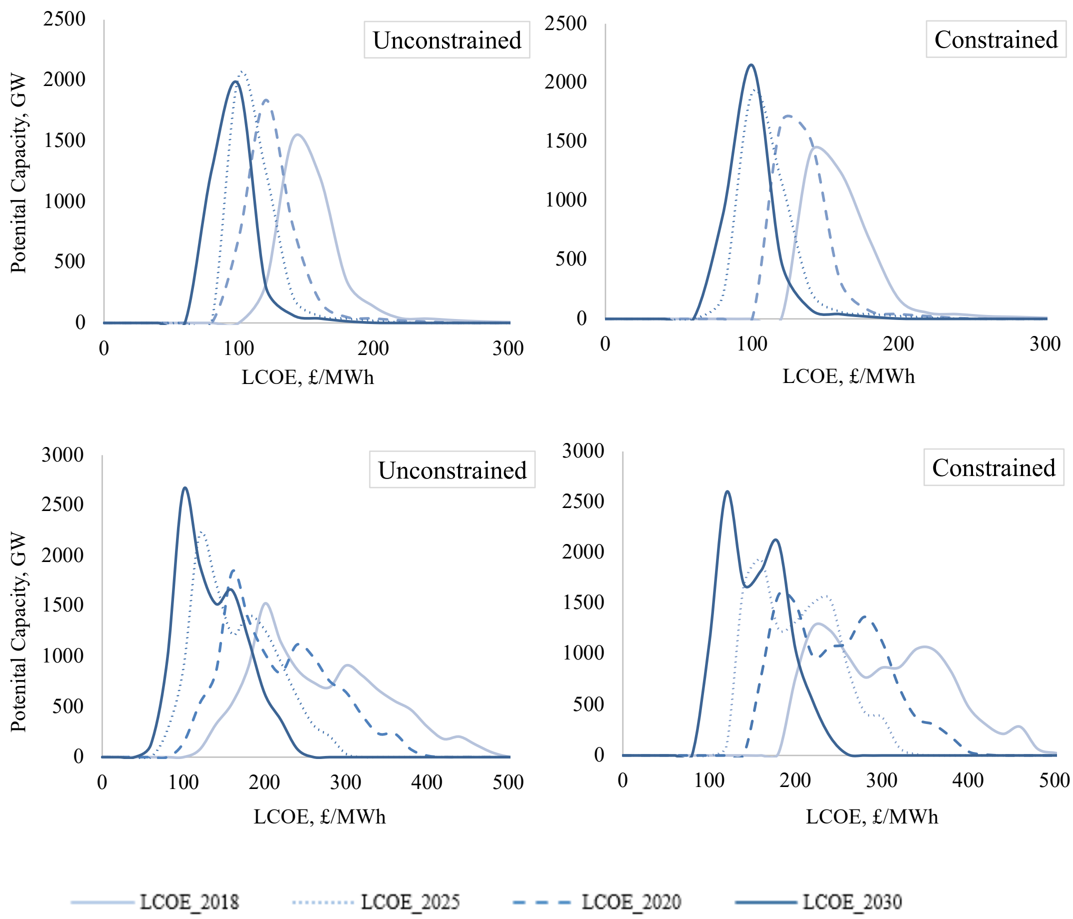


Figure 46. Potential floating wind (top) and wave (bottom) capacity available in cells against cell cost derived LCOE's for each forecast. Significant peaking is observed which represents the maximum capacity that could be installed in the available area.

As expected, the distributions are positively skewed towards lower costs of energy across both technologies. What was also discerned was that in early forecasts there are larger dispersions resulting in wider kurtosis. This was due to more variable site characteristics affecting cost. Convergence of results were also visible in the volume of potential capacity with wind being more focussed as well as cheaper. This has been attributed to the increased performance and availability parameters set in the model. When comparing the two technologies variability was observed in the form of the statistical shapes. Twin peaking was seen in the wave technology plots which demonstrates occurrences where wave devices have filled the area suitable for the potential GW capacity at a given cost. While the area between the peaks represents a lack of suitable space at cost for the wave energy arrays in the study area. The tertiary peak representing more capacity for deployments but at a higher cost.

6.3.2 Spatial Distributions

The spatial distributions of the LCOE data represents a further understanding into infrastructures significance to industry development. By deriving a ratio between the two, constrained and unconstrained, LCOE models the locations for the most significant change can be observed, as seen in Figure 47.

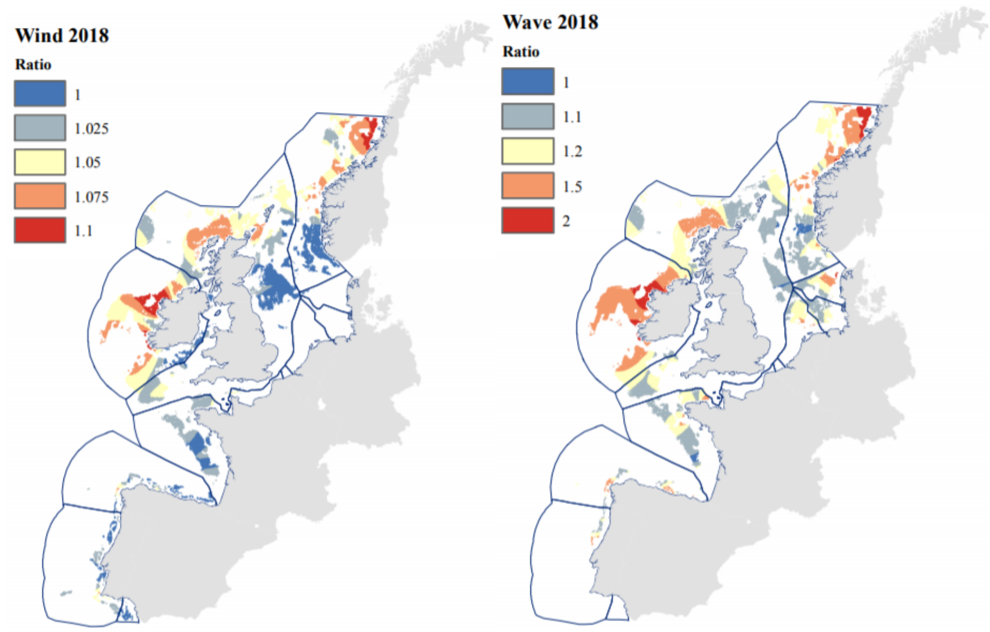


Figure 47. LCOE ratio of constrained and unconstrained models for wind (left) and wave (right) in year 2018. With higher ratios in red demonstrating the largest convergence.

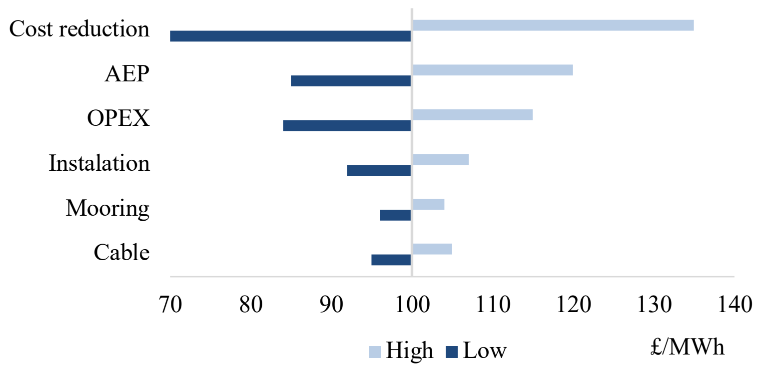
Wind demonstrated a significant change in the northern Atlantic coasts of western Scotland, Ireland and Norway, while being limited for the rest of the study zone. Similar convergence was seen for the wave technology. However, further groupings were observed off the coast or western France, Denmark, Spain and Portugal. While for both, cold spots could be seen in the central to western North Sea, the Bay of Biscay and southern Portugal and Spain. This indicated that the most significant locations for cost reduction could be targeted. These outputs as well as the LCOE values in 6.3.1 both demonstrated a clear answer to research question 4, does existing port and grid infrastructure affect the selection of sites for exploitation? While sensitive to annual energy production and site parameters a comparison could be made to the significance in the location of infrastructure. However, this demonstrates the direct link between distance and cost. To accurately reflect the practical limits of infrastructure the suitability to connect and service arrays must be assessed.

6.3.3 Sensitivity Analysis

Due to the nature of making cost predictions, the sensitivity of these variables had to be addressed and their impact on LCOE measured. A high and low case sensitivity margin was applied to each of the cost variables and the AEP values considered in section 4.5.2. The margins of error for the inputs in the cases are presented in Table 7. The plots in Figure 48 demonstrate the variation for wave and wind respectively for a 2030 forecast.

Table 7. LCOE% error range approximations for both technologies and each cost component considered.

	Wave		Wind	
Type	Min	Max	Min	Max
Cable	7	7	5	5
Mooring	7	7	5	5
Installation	12	12	10	10
OM	15	15	10	10
AEP	7	13	5	7
Cost reduction	25	25	15	15



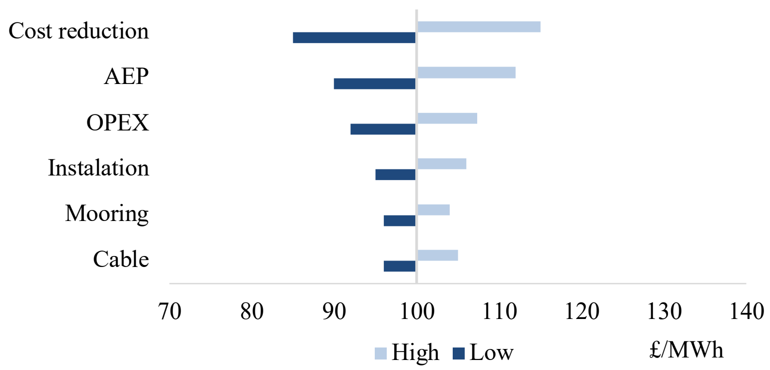


Figure 48. Tornado sensitivity plots for wave (top) and wind (bottom) cost variable impacts for forecasted 2030 values.

What becomes clear when comparing both plots is the increased sensitivity of the wave compared to wind. Increased magnitude for wave was observed with variations for AEP of approximately 25% in LCOE compared to 11% for to wind. The largest deviation in sensitivity for both technologies remained the cost reduction factor which was known to be significant. However, as this factor was applied to all scenarios the relevance is minimal as the site dependant factors are more significant to this assessment conducted in this thesis and was used as an indicator of cost. Further exploration of the cost reduction factor falls beyond the scope of work. As expected, there was a larger cost increase with reduced AEP values as productivity might be more affected by poor production. The factors of, installation, mooring and cabling all had less than 10% sensitivity in LCOE. These cost sensitivities were factored into further analysis as to be discussed in section 7.7.

6.4 Chapter Summary

This chapter defines the process to establish the levelised cost of energy (LCOE). It considered the capital expenditure (CAPEX) and operation expenditure (OPEX) in relation to the energy production seen at each cell in the study area. The method used takes into account the site driven cost variables that impact LCOE. The process applied site factor curve functions to allow for site-based analysis. Further, the model considered varying cost reduction factors that may impact the technology LCOE over time. These cost reduction factors were crucial in the site assessments as it was assumed that more sites will become economically viable over time. Through this method it was therefore assumed that technology roll out is only considered when technology were at levels of economic viability for the timeframes considered. It therefore does not consider the cumulative impact of technology development on cost. The chapter continues to discuss the two main infrastructure types that were assessed within this thesis, those include the location of, ports and the electrical grid. The modelling work considered two approaches to cost assessments for technology. Those include, the constrained cost of using known infrastructure locations and the unconstrained cost of a 'best' case scenario. The latter output of unconstrained LCOE considered how the technology may be more feasible if infrastructure were tailored to any desired location.

7. Infrastructure Analysis

Abstract: In chapter 7 a spatial allocation method is demonstrated which seeks to identify relationships between array locations of the floating wind and wave technologies and theoretically suitable infrastructure. Further the factors influencing grid connection and port suitability are explored in two analytical models.

7.1 Introduction

Within this thesis the two types of infrastructure, ports and electrical, were assessed for their role in influencing cell costs, as illustrated in Figure 49. The preceding chapters sought to address the site-based parameters that contribute to the overall assessment of the hypothesis. The primary research questions into the topics of where the industry might be successful has been assessed. However, to establish the cost-effective locations viable for large scale floating WWE developments the capability of infrastructure connections must also be established. By doing so a spatially and capability dependant assessment LCOE can be made.

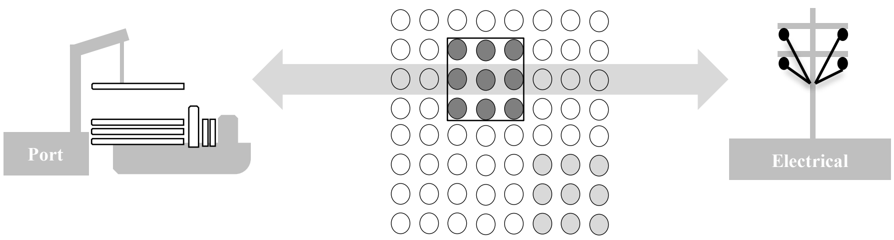


Figure 49. Diagrammatic of allocation processes of a selected array within the cell matrix to port and electrical infrastructure

The distance to array locations was, as presented in the preceding chapter, a key cost driver. However, the question of suitability of infrastructure and the role in which capacity of grid connections and the capabilities of ports was significant. In many cases ports are not fit for operations and grid connection points cannot transmit the volumes of power being produced.

Therefore, to assess the LCOE relationship between array's and infrastructure, research question 5 was developed to explore the research gaps associated and was defined as:

5. How would infrastructure capability alter overall deployment areas and associated costs?

Work demonstrated in [126] explored the roll of location sensitive spatial modelling in an allocation model, where quantities of a product were allocated a location, for the offshore wind sector. While exploring offshore electrical infrastructure designs the research demonstrated the clear use of this type of modelling process in making multi criteria assessment. This chapter addressed the research question in two forms, first a static allocation based on theoretical capabilities and second a more practical assessment considering 'real world' situations. The latter analysis utilised two external models separate from the allocation process and focussed on the wider European energy market and practical development factors.

7.2 Modelling Process

Resolving the research questions demanded a spatially constrained allocation model to relate location to infrastructure. The processes were performed in ARC GIS using the network analyst tool package. Demonstrated in Figure 50, the process was based around two core allocation models, array grouping and infrastructure allocation. The theoretical allocation volumes and sites were then tested in two analytical models, Port and Grid analysis.

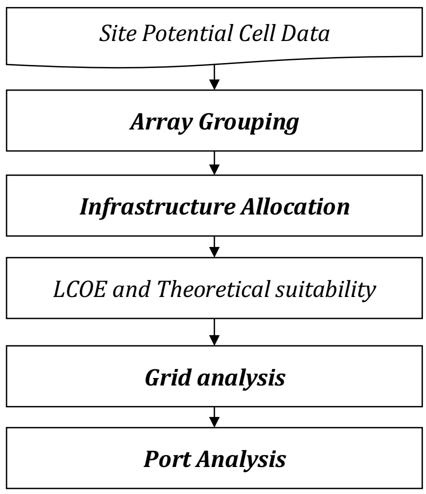


Figure 50. Modelling overview with main sub models to establish infrastructure dependent LCOE. Where output potential data from site assessments were used in subsequent modelling processes.

The first model, array grouping, combined the hotspot site data from the proceeding chapter and grouped cells in bins around of pre-determined sizes. The arrays were connected to infrastructure nodes using an offshore network, details of which are presented in 12.5. It was along this network that shortest distance routes to infrastructure were established. The second model allocated volumes of array 'product' to grid connection points and ports. The capacity and location of these infrastructure points were approximated in further modelling work as to be discussed.

By combining these spatial analytical processes, the proportional distribution of both power to the grid, and devices to be serviced in ports, were estimated. The distance to the two forms of infrastructure were assessed and the output of which used to perform further LCOE analysis. Grid analysis was performed using a genetic algorithm to identify the volume of power from sites that could be connected to the grid based on the European energy mix. This analysis considered market constraints and production variability in two separate models for wave and wind technology. These sites were then allocated a port and the time taken to build out developments evaluated. Here the distance to site, operability windows and installation times were considered and a timeframe for developments assessed.

7.3 Array Grouping

The spatial analytical processing performed in the infrastructure allocation model contained certain computational constraints due to the large amount of data being assessed. The ceiling for the software was approximately 30000 cells, where the total number of cells under analysis was approximately 250000-300000. Therefore, reduction through array grouping was necessary. As was discussed in section 4.4 the converter cell density over 2km provided varying levels of rated power production. The number of cells were reduced through binning cells into array clusters of increased capacity. By grouping arrays through applying the coarser resolution the overall computational problem of allocation was made workable.

7.3.1 Array Characteristics

The sizing of the cluster was determined by the technology suitable for the transmission of power to shore. This involved the collection of power produced by the converter and pooling to central grid connection points. This thesis assumed that the technology was similar to the type of configurations seen in the fixed offshore wind sector as represented in Figure 51.

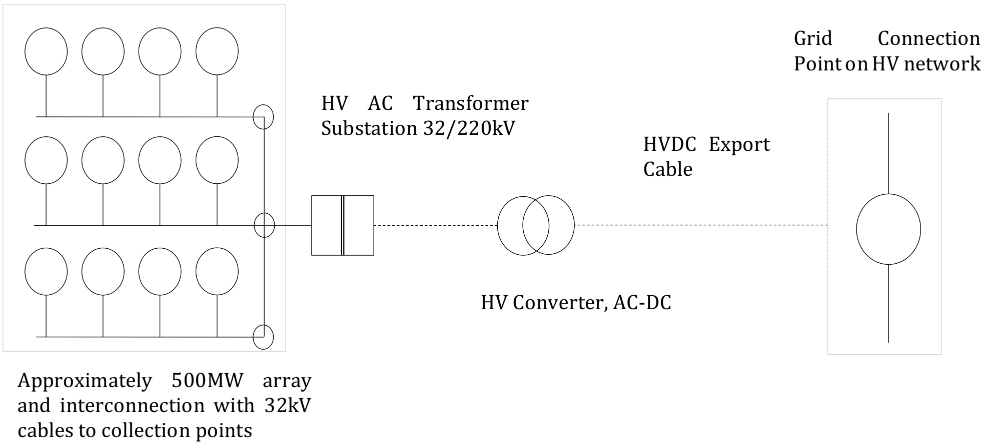


Figure 51. Electrical infrastructure diagrammatic of generation from array of 500MW to coastal grid node and the HV network.

The process depicted was similar to the work in [126] and was used but under one fixed configuration. An assumed 500MW rated capacity cluster was assumed for each array collection point, sub-station. This has been observed as a progressive benchmark set by the wind industry as observed in [148] where large scale fixed wind arrays range between 100 and 500MW per substation. Work in [34] [104] demonstrated that a floating wind farm cluster would also fall into this range if made to full scale commercial adoption. Similar was assumed for wave energy across all scenarios. Therefore, each grouping must fall between a range of approximately 100 – 900MW of a single or dual substation grouping.

7.3.2 Minimise Facilities

The first location allocation model to be solved performs the grouping of cells to central collection points. The algorithm, 'minimise facilities', was applied here which seeks to satisfy the objective of allocation as many cells of, 36MW (wind) or 100MW (wave) size to facilities within a constraint, 'impedance cut off' distance. The distance cut off value was defined as, the total distance from cells to substation from the cost path. An exponential transform was chosen to favour lower distances at each cluster. The algorithm further aimed to solve under another constraint of using as few array substation points as possible. Therefore, creating a solution which was representative yet more computationally manageable. The impedance value determined the physical size of the array and therefore was set to best reflect the rated output within the range of 100-900MW. For wind this distance was set to 6000m while wave was 3500m, the former being larger due to the density of converters in each cell. The preceding hot spot models output from section 5.7 were used to determine the weighting for each array grouping. The allocation model therefore solved to find the group of highest performing cells first. The output of which, Figure 52, was a series of offshore cluster locations with favourably weighted towards the study aims.

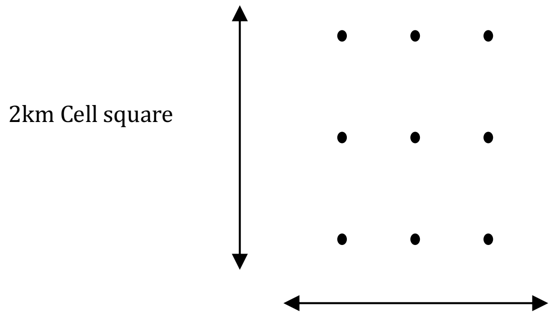


Figure 52. Lines from demand cells at the 2km resolution to substation grouping points at courser resolution.

After assigning hotspot data and using only suitable sites the approximate number of demand locations was between, 250000 – 300000 cells. While the substation matrix at 5km was approximately 20000 locations. The model iterated through multiple times to find each solution for the time frames, the results of which are demonstrated in

Figure 53.

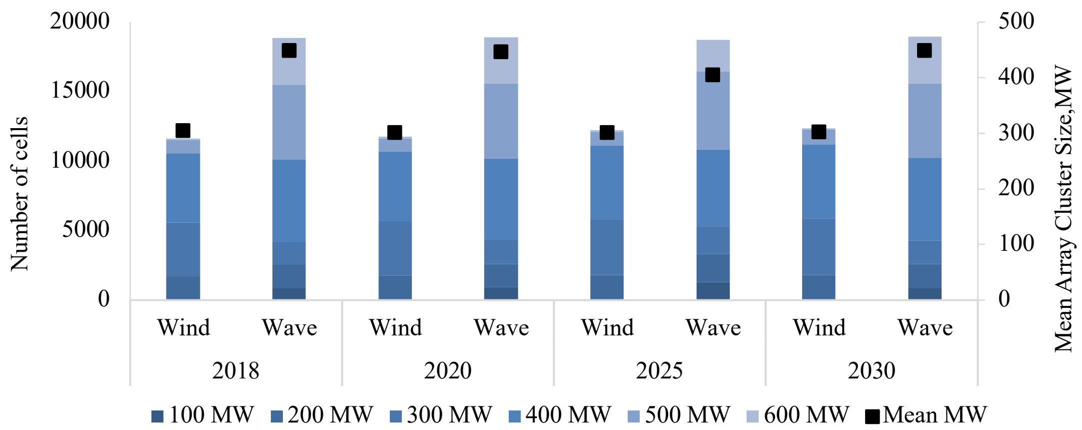


Figure 53. Array cluster size outputs. Each forecast and technology was represented and the number of cells indicates the greatest coverage of a given substation MW size. Larger capacity substations had a higher cell cover count and could be deemed more suitable. However, the largest size substation excludes the largest number of cells and cell coverage was maximised around the mean value. The mean value was indicated for each technology and ranges between 300MW and 450MW in size.

What was observed from the outputs was a dominance in both technologies of medium sized substation groupings of 300MW for wind and 400MW for wave. Current deployments for fixed wind have been discussed as being larger than this mean and that wave energy technologies have not yet seen array development. However, in this thesis the assessments made were based on the fact that array size and configurations have reached this type of commercial level of deployment.

The increase in magnitude between wind and wave was due to impedance distance being greater for wind to cover a larger area.

7.4 Infrastructure Assessment Methods

The second model outlined in Figure 50 incorporated the two forms of infrastructure to be assessed, port and grid, connection with the array locations. To assign volumes of devices and power of array clusters to these facilities required an assessment and understanding of the limits of connection capability. The allocation model utilised two infrastructure variables to perform analysis, capacity and suitability rank.

As discussed in the previous section the size of the mathematical problem for spatial allocation modelling was restricted by the number of facilities and demand points being considered. Furthermore, the requirements in the market modelling solver, presented in section 7.8, also had a limit of inputs of approximately 100 nodes. Therefore, simplification of the Western European grid system and its associated, generation, demand and transfer capabilities at a coastal level were undertaken. A novel simplification process was developed to reflect the requirements of the industry and the suitability for allocation modelling.

7.5 Grid Simplification Modelling

The primary objective of this work was to reduce the Western European grid components used in allocation modelling to be made computationally manageable. A spatial analytical process was created to perform aggregations which reduced the regions into a series of clusters. Similar approaches have been discussed at length in section 1.6.10. The processing included, demand, generation, resource, network and operator data for current and forecasted time frames. This novel method was developed for the bespoke requirements of the industry, tailored the network towards the needs of the floating industry. Following this approach allowed for more detailed analysis of the industries connection requirements at a finer coastal level to a more granular level.

The European Network of Transmission System Operators for Electricity (ENTSOE) ten year development plans (TYDP) of 2018 and 2016 were used for analysis and the forecasts for: 2020, 2025 and 2030 topologies and energy mixes utilised. Generation and demand levels used the model outcomes from the TYDP of: ‘Best Estimate’ (BE) reflected the network system operators (NSO) perspective at a national level with EU regulations and the goal to forecast reduced coal and estimated gas prices. In 2030 a range of forecasts were estimated by the EU, these include: ‘Sustainable Transition’ focusing on fast and economical CO_2 reduction. ‘Distributed Generation’ examines a decentralised development of energy and EUCO. EUCO, a European Commission energy forecast, represented a core policy for reaching 2030 energy targets agreed by EU states.

A mean estimate was made across the scenarios to represent 2030 in the models. These data sets forecasted the trend in generation and demand levels as well as cost.

7.5.1 Market Nodal Data

The sub model demonstrated in Figure 54 assigned data to each geographical regional boundary zone, Nomenclature of Territorial Units for Statistics (NUTS) polygon which represented the statistical regional boundary from a community to national state level for each of the study countries. The data used fell into two categories of requirement: 1) generation and demand data used in the global power modelling system, and 2) the coastal requirements for floating WWE Technology and subsequent grid aggregation.

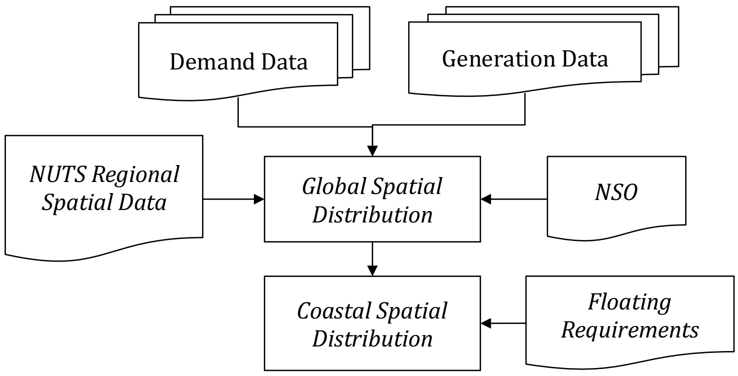


Figure 54. Regional data types spatially distributed at two levels.

The global data of generation, demand and NSO were proportionally distributed on a NUTS regional level. The characteristics for floating WWE that impact power generation and transfer included resource quality and depth. These input into provided a series of node points containing the aggregated data.

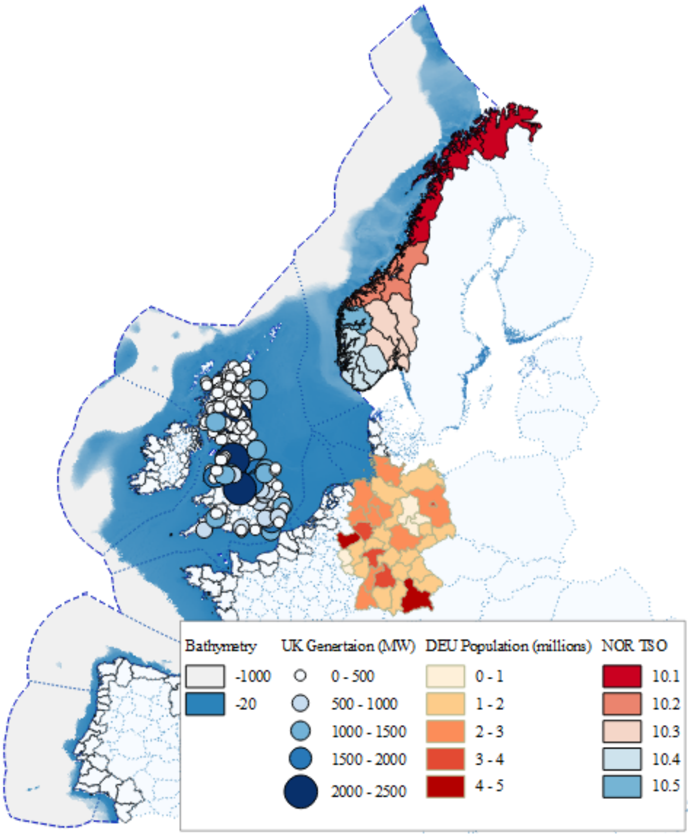


Figure 55. Demonstrative data inputs selected in grouping analysis for floating WWE requirements and NUTS regional boundary polygons. Where DEU was the German population distribution example used in the German case. NOR TSO was the example of Norwegian transmission operators grouping used for validation in the Norwegian case. The UK's generation capacity distribution represented in terms of MW.

Overall Distribution: The study, Electricity Sector Data for Policy-Relevant Modelling [89], demonstrated an approach to distributing energy data. These methods as well as those in [42] were considered in establishing regionally normalised data. Demand values were assumed to be proportional to population. Therefore, demand was estimated from NUTS regional distribution of a European population dataset from Eurostat and the ENTSOE national power demand data sets. Future demand from the Ten-Year Development Plan (TYDP) was used to normalise the distribution to the forecasted levels. Generation installed capacities were obtained from national statistics database in ENTSOE [81]. Table 8 outlines the generation and demand data assumed for each country.

Table 8. Installed rated generation capacity and demand for forecasts and study countries over the four time frames considered.

2018	BE	DE	DK	ES	FR	UK	IE	NL	NO	PT
Biofuel	823	7245	1178	744	1045	1377	0	486	2	615
Coal	0	47681	4550	10004	2997	15450	1083	4608	0	1756
Gas	6546	28541	2431	32323	11679	30600	4215	19297	445	4657
Hydro	1430	10172	8	20353	23751	3920	530	38	30767	6945
Nuclear	5926	10793	0	7573	63130	9230	0	486	0	0
Oil	160	4889	839	3425	7130	880	916	0	0	42
Other Non	0	3008	44	0	0	0	0	0	0	0
Other Res	0	38	0	0	0	0	0	0	0	0
Solar	3087	40021	851	6973	6772	11500	0	2039	0	439
Offshore Wind	712	4126	1271	0	0	5000	0	638	0	0
Onshore Wind	1580	45404	3978	23057	11762	10000	2740	3479	869	5046
Total Gen.	20264	201916	15150	104452	128266	87957	9484	31071	32083	19500
Demand	9680	61495	3893	30605	55023	37078	3219	13174	15263	5662

2020	BE	DE	DK	ES	FR	UK	IE	NL	NO	PT
Biofuel	905	7969	1296	818	1150	1515	0	535	2	676
Coal	0	48760	1179	9533	2900	7392	850	4608	0	576
Gas	5400	28166	1772	24948	6951	36842	3434	11772	425	3829
Hydro	2003	17540	7	24679	26373	2782	676	38	33054	9459
Nuclear	2963	5397	0	7345	57665	6973	0	486	0	0
Oil	80	2880	828	1713	4262	883	620	0	0	21
Other Non	0	6070	72	0	0	0	0	0	0	0
Other Res	0	3633	0	0	0	0	0	0	0	0
Solar	3817	48835	1366	14587	14165	15327	0	4796	0	1128
Offshore Wind	1511	7713	1994	0	0	11065	0	3569	0	0
Onshore Wind	2218	50452	4475	25978	19049	13380	3770	4859	1985	5300
Total Gen.	20502	214233	14396	115382	138214	98808	10290	34769	35518	22409
Demand	9844	61965	4533	31283	54533	37448	3527	13220	15808	5791

2025	BE	DE	DK	ES	FR	UK	IE	NL	NO	PT
Biofuel	1086	9563	1555	982	1380	1818	0	642	2	811
Coal	0	32317	410	4660	0	0	1051	4548	0	1180
Gas	5989	27643	430	24560	11496	30685	3724	8452	435	2839
Hydro	2575	24908	7	29005	28994	1644	822	38	35342	11973
Nuclear	0	0	0	7117	52200	4715	0	486	0	0
Oil	0	871	817	0	1394	886	324	0	0	0
Other Non	1157	9132	99	8070	0	10989	160	4086	0	1052
Other Res	658	7229	700	1800	2684	7697	114	507	76	843
Solar	4547	57650	1881	22200	21558	19153	100	7552	0	1816
Offshore Wind	2310	11300	2717	0	3500	17130	0	6500	0	60
Onshore Wind	2856	55500	4971	28900	26336	16760	4800	6239	3100	5554
Total Gen.	20741	226550	13642	126312	148162	109659	11095	38467	38953	25317
Demand	10007	62434	5173	31961	54042	37818	3836	13267	16354	5919

2030	BE	DE	DK	ES	FR	UK	IE	NL	NO	PT
Biofuel	1304	11476	1866	1178	1656	2181	0	770	2	974
Coal	5	28301	764	3158	1260	167	334	0	1	0
Gas	7464	25718	406	25680	9343	31244	3567	8522	911	3733
Hydro	2575	24840	7	31330	32994	1895	1100	38	36932	13321
Nuclear	0	0	0	7211	44924	8160	0	486	0	0
Oil	239	972	617	984	3336	1427	424	689	1	333
Other Non	771	7438	66	5732	207	4302	107	2504	5	701
Other Res	439	4421	467	1700	2441	5492	233	338	51	562
Solar	2302	27168	279	12189	9540	3677	6	1978	267	709
Offshore Wind	2620	13282	2881	21	6678	19230	510	8520	613	49
Onshore Wind	3581	58967	5488	32178	30608	20655	5366	7040	3454	5986
Total Gen.	21300	202582	12841	121361	142987	98430	11648	35432	42237	26368
Demand	10403	63967	5193	32243	54876	40360	3966	13958	17232	6140

The location of generation type and capacity was established by combining the data sets of ENTSOE and Enipdeia, an open source electrical geo database, and geo-locating each generation station over 10MW capacity resulting in 809 locations. Owing to discrepancies between datasets the demand data and installed capacity were scaled to sub ENTSOE national values with a pre-normalisation mean of 76% and 82% respectively with a 92% and 88% representation post-normalisation. Spatial distribution variation in sub-national values were found across regions due to data clarity. However, total installed capacity was matched with ENTSOE values and local generation capacities were relatively scaled.

The types considered in the analysis alongside WWE were taken as dispatchable and non-dispatchable power. Dispatchable units were defined as generation types, which can adjust power production including Nuclear, Hydro, Biofuel, Gas and Coal, while Solar, Onshore and Offshore fixed wind were considered non dispatchable. Some types of future generation were provided by the two datasets however, they were incomplete due to data sensitivity and access. Therefore, several key estimations had to be made to distribute these future generation levels. As was proposed in [89] and [42], similar data analytical methods was taken in this work. It was found that future thermal plants will most likely be located near existing plants and infrastructure. Therefore, existing geo-located plants were scaled accordingly. The TYDP reports outlined the development of significant Hydro electrical installations in future which have been included.

Renewable Resource: Similarly, to the E-Highway study assessed in section 1.6.7 variable generation types, such as solar and wind were more variable in location and require a reflection of the quality of resource. The level of installed capacity was correlated with the level of resource available within the country in question. To reflect solar and wind power potential capacity, an annual mean value per NUTS region was established from two EU Joint Research Centre studies. Solar irradiation values were obtained from the study solar radiation dataset [149], and monthly wind speeds from the MAPPE model [150]. Future fixed offshore wind values were grouped to the connection points already established, as these pre-existing values represented the beginning stages of national development tranche clusters such as the UK's round 3 sites. However, these values were limited to levels of those known clusters in immediate or imminent completion. For the purposes of the network simplification modelling a mean value was used. Furthermore, the same datasets were used to created seasonal, summer and winter and diurnal, day and night, dataset for application in market modelling.

Coastal Distribution: The coastal granularity was defined as every polygon with connecting access to the marine EEZ. However, as the offshore resource was known to be variable, not all coastal regions were of the same significance. Therefore, a process to determine key sites was established. The foremost grouping consideration for WWE characterisation for the offshore renewable types was considered as the wind and wave resource available. Resource characterisation was established from data [28] provided by the University of Athens. As an approximation of resource, an annual mean was estimated for wind speed, ws, measured at 100m and wave power as kW/m. Coastal related resource bins, Figure 56, were characterised as an offshore radial parcel at a distance of 400km, unless interrupted by land. The maximum resource values of each bin were then established. Each location contained a secondary value of depth, which was used to filter out data beyond a general scoping range of floating WWE feasibility of a maximum of 1000m and a minimum 30m. These values were based on the minimum draught of floating technologies being proposed [18] [102].

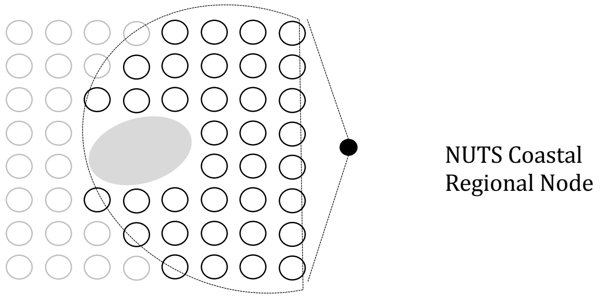


Figure 56. Offshore resource data parcel search method within the respective marine EEZ. Resource points of over 50% coverage were included in analysis.

As was seen in [42] the need to justify aggregations was determined by the validity of the reduced system. In the study, grid managers were consulted to assess network parity. In this work, the same justification was made by defining regional boundaries defined by NSO (Network system operator) or TSO (transmission system operator).

7.5.2 Regional Grouping

For both wave and wind requirements regional granularity, grouping was performed. After prerequisite regional data were analysed, each national focus area was modelled based on spatially constrained variables to find the optimal distributions of regions. These values were then used as a constraint in a balancing algorithm developed to solve for aggregated demand, generation and RTC. This was conducted to ensure that the system would be more accurately representative of a 'real' system. The modelling flow process established in GIS has been defined in Figure 57.

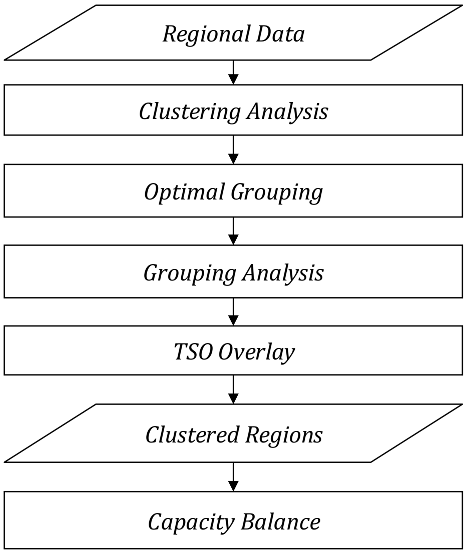


Figure 57 Grouping sub model flow process with both sets of geo spatial analysis represented as sub models. Grouping and grouping balancing represented as two processes.

The clustering model used a grouping analysis toolkit in GIS, similar to methods seen in the E-Highway study and [89]. The spatial analytics *'K nearest neighbour'* grouping algorithm has been applied. The algorithm assessed a multi variate problem for the closest correlation of spatial data. The constraint of the mean K nearest neighbour, representing the mean of the closest distance to a number of neighbours, was established through a connectivity graph to find groupings. The objective function solved for the correlation of best resource characteristic for wave and wind within each country's coastal region distribution and the national NSO boundary groupings. At a European level, this was made relevant on a 0-1 scale through a min max normalisation. The algorithm was solved initially to determine n, the optimal number of groups, to satisfy variation in normalised resource, values which have been demonstrated in Table 9.

Table 9. Grouping values to identify optimal number of groups, with the original NUTS node, n, count and reduction after processing for both wave and wind. Correlation demonstrates the relationship of the spatial inputs and the output NUTS grouping.

Country	NUTS a	Wave n	Wind n	Correlation
BE	11	2	4	0.74
DE	40	8	8	0.68
DK	14	3	4	0.8
ES	47	10	8	0.72
FR	96	13	8	0.59
IE	26	4	5	0.75
NL	14	5	4	0.62
NO	19	5	5	0.82
PT	18	4	5	0.61
UK	192	16	8	0.62

In most cases the model sought to distribute more nodes to wave energy. This was particularly strong in the countries with a high resource potential, the UK for example. However, the dominance of resource was shown through this modelling. However, the NSO boundaries also had an impact through the restriction of the number of nodes. Countries with, a favourable resource (Ireland) a dominant NSO region (Norway), or limited coastline (Germany) demonstrated the reduction in node numbers. NSO regions were used to group those values not significant to the coastal granularity. However, in events were NSO boundaries were unsuitable, regions were split by means of least conflicted connection as depicted in Figure 58. In most cases NSO groups could be defined.

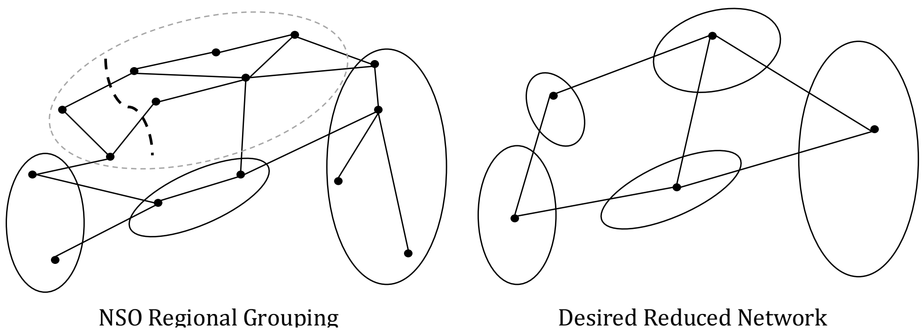


Figure 58. NSO groupings and network links grouping. Divisions were made where the minimal numbers of links and node junctions were located.

Where low dispersion in correlation, <0.50, exists, n wave and wind were treated as one node. The final optimal n was returned to output the spatial grouping of polygons. Regions created groupings based on spatial data. However, in order to ensure model viability a balance of sum, demand, $NUTS_d$, generation, $NUTS_g$, and regional transfer capacity, RTC, was established as:

$$\sum NUTS_d - \sum NUTS_g \leq \sum NUTS_{RTC}$$

Equation 17

Where values do not satisfy the criteria, they were absorbed into the nearest region with most transmission connections and results were rebalanced.

7.5.3 Topology Creation

The Regional Transfer Capacity (RTC) in MW was estimated in this work as the exchange between geographical regions. In order to estimate RTC the physical capacity of lines between potential clusters was established. The line characteristics were used to determine the surge impedance loading (SIL). The RTC model used open source SciGrid data from the GRIDkit study in [147] for analysis. Figure 59 illustrates the logical flow of the topology aggregation conducted.

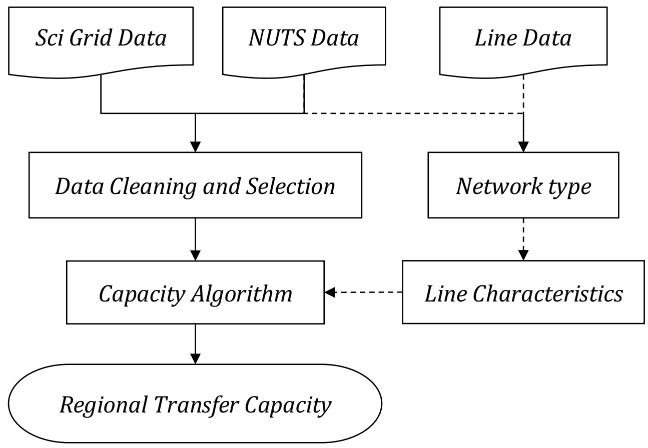


Figure 59. Transmission Line Topology, data cleaning sub model and flow limit estimation with SciGRID and NUTS polygon inputs.

SciGRID utilised OSM (Open Street Map) data to identify power lines and associated systems. The extracted data however relied on the robustness of OSM data. Although, it has been assumed that the data was representative of large-scale transmission systems and therefore suitable for this type of analysis. Components represented included, length, kV rating and configuration of conductors. This data was cross referenced with the ENSTOE grid atlas to ensure a closer representation of location and circuit type, as well as to replace missing data from SciGRID. The level of detail missing was, at a level that falls beyond this work's scope and therefore it has been assumed as negligible.

Filtering was conducted around a set of criteria for the spatial analytic NUTS regions and line types. The line kV types fell into several distinct categories, this was also identified from ENTSOE datasets and [151]. Therefore, the filtering model selected these lines for analysis. These high voltage ratings ranged from 220 – 700kV, however key smaller cross region border voltages of 150kV were also accounted for. The process of filtering multiple line systems to be represented as single lines had inherent complications. This was also noted in [152] where type kV splitting of several lines for one link, for example, a 400/110kV line becomes complicated in the spatial analytics model. In these cases, they were treated as separate circuits of 400 and 110kV and modelled accordingly. Another line filtering 'irregularity', also noted in [152] [153], was the spatial segregation of splitting of merged lines as pictured in the Figure 60.

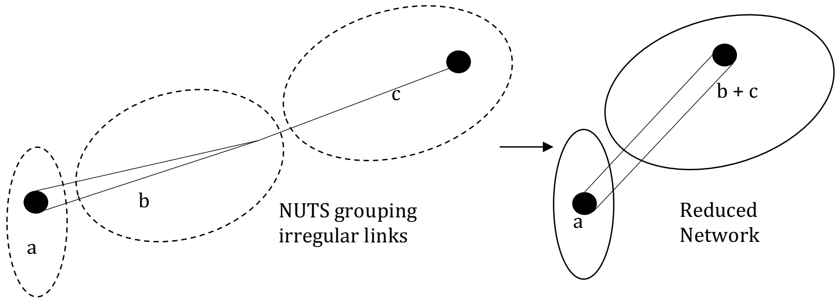


Figure 60. Grid reduction method using NUTS defined geospatial zones as network zonal boundaries over reduction.

However, this problem was solved by the modelling process through amalgamating zones as representations of one entire system. Where the connection from a to c travels through b in its pure network, the grouped zonal system simply represented the new relevant link between a to bc.

The SIL estimation method applied was known to be suitable for lines above 80km in length [154] [155] [156]. SIL was used to establish the flow limit according to the characteristics of the lines. This value was an approximated representation of a snapshot of power flow delivery of the natural uniform loading on the lines in question. It assumed that the line has no net reactive power flow or resistance and has an approximated flat voltage profile. SIL, established from [155] has been equated as:

$$\text{SIL (MW)} = 0.927 * \left(\frac{\text{kV}^2}{\text{Z0}}\right)$$

Equation 18

$$Z_0 = \sqrt{\frac{\text{Lc}}{\text{C}}}$$

Equation 19

Where, *kV*, represents the transmission line voltage rating from the SciGRID database, *Z0*, the surge impedance on the line and a relationship of capacitance, *C*, and inductance, *Lc*, over distance, *L*. Two main line characteristics were assessed to derive capacity, geometric mean radius (GMR) and geometric mean distance (GMD). Capacitance and inductance being approximated from [154] [157] and in [155] as:

$$\mathrm{Lc}\left(\frac{\Omega}{\mathrm{km}}\right) = 2 * 10^{-7} * \ln\left(\frac{\mathrm{DMR}}{\mathrm{GMD}}\right) * \mathrm{L}$$

Equation 20

$$\mathrm{C}\left(\frac{\mu\mathrm{f}}{\mathrm{km}}\right) = \frac{2\pi\varepsilon 0}{\ln\left(\frac{\mathrm{GMD}}{\mathrm{GD}\frac{\mathrm{b}}{\mathrm{s}}}\right)}$$

Equation 21

Where $GD\frac{b}{s}$ represents a geometric relationship of the bundle or simply the radius, r, of the conductor in question and ε0 is a constant of the permittivity of free space. Geometric characteristics were established to create a line configuration database. These design approximations have been represented in Figure 61. An assumption that all line types follow these geospatial estimations has been made, as well as the use of a singular un-transposed asymmetric 3 or 6 phase bundled cable pattern for all lines.

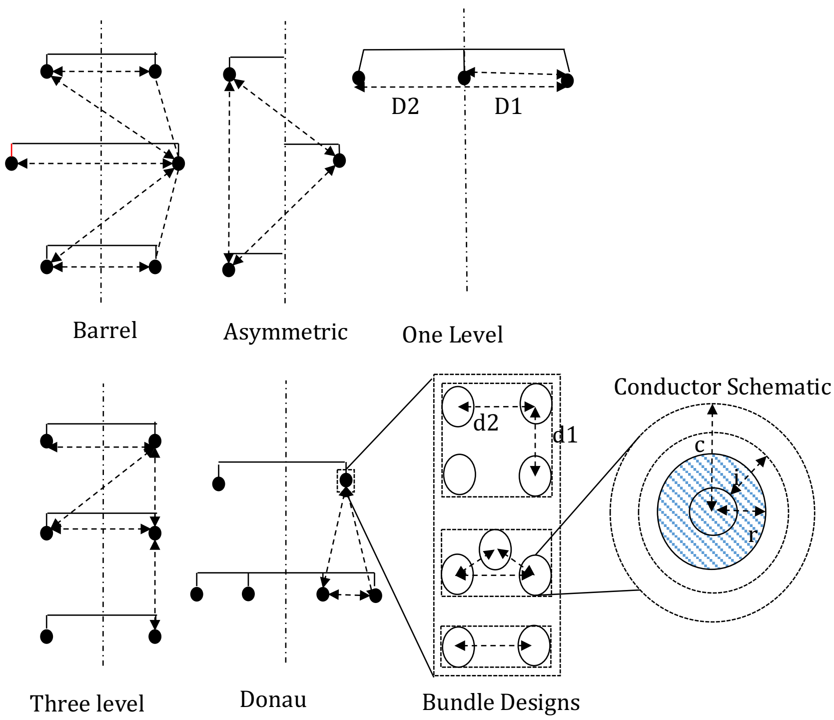


Figure 61. Common transmission line configurations according to OSM, national and network operator data.

Due to the geospatial reduction of larger line links, several cases were found where line lengths fell shorter than the SIL approximation was deemed accurate, this was highlighted in [155] [156] [158]. This limitation was due to the line fundamental thermal limit. This characteristic can be evaluated through the use of the St. Clair plot relationship, Figure 62, which related power transfer capabilities through the relationship of SIL and thermal limits. It was noted in [156] that load ability characteristics could be established from this relationship at approximately 3 times the surge impedance loading. Similar approximation was concluded in [155] and in [154] where it was shown that stability limit restrictions decreases over length. Therefore, from plotting stability limits for lines less than 80km, a polynomial function was derived and applied to these 'short' lines.

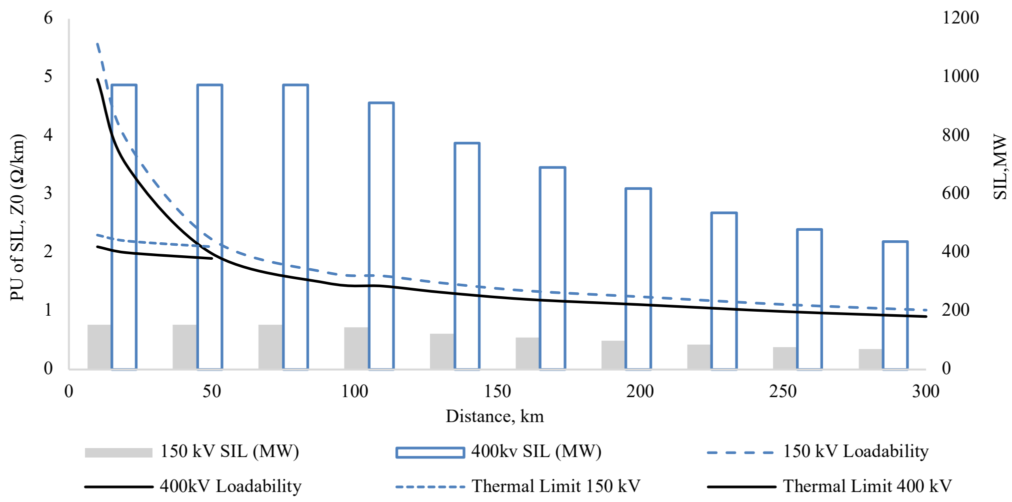


Figure 62. St. Clair plot of 150kV and 400 kV lines with the correction of 3 * SIL. A fourth order polynomial was established as: $y = -2E\text{-}09x^4 + 1E\text{-}06x^3 - 0.0002x^2 - 0.0052x + 3.1432$

After scaling lines accordingly, the inter NUTS regional RTC was established and capacities merged. An original 11858 were filtered to 1623 being input into the RTC functions returning the following: 266 (2018), 272 (2020), 280 (2025), 275 (2030) regional transmission links.

7.5.4 Simplified Distribution Boundaries

To simplify the nodal system while maintaining a geographic representation of the regional NUTS aggregations they were validated against the NSO boundaries. The analysis shows an expected decrease in estimated line flow as cluster size decreases and the opposite as lines increase. Figure 63 illustrates the change from original NUTS distributions to the clustered output used in the analysis.

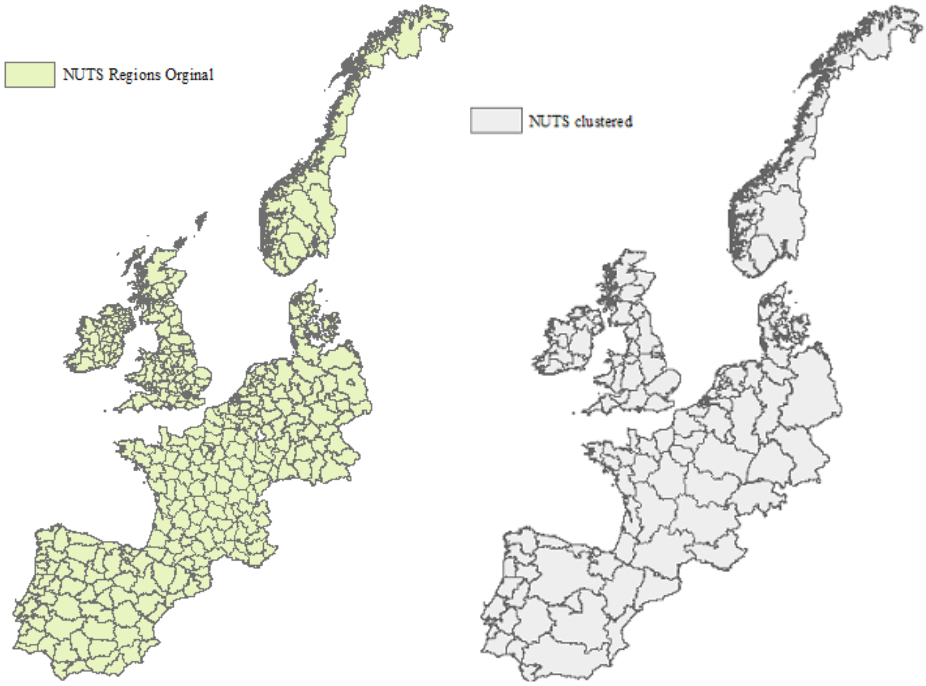


Figure 63. Clustering outputs from original (left) to the reduced coastal system used in analysis (right).

The variability in resource across the data was evident when considering the resource and depth data where clusters were heavily skewed towards the coast. Depth and resource constraints have an impact on grouping where relative node values were found to be shallow, or resources poor. This was seen in the Netherlands and Belgium where water depth was extremely limited which results in the model aggregating these clusters to the minimum. This was clear when comparing both plots for resource types where wave showed a higher correlation due to lack of depth and therefore smaller variation in coastal wave climates. Similarly, the variation in groupings due to the NSO regions and network connection were, as expected, minimal. The variability across countries showed further sensitivity for resource values and grid connection, Germany for example has a well-connected grid but poor resource access and therefore was clustered more uniformly to its NSO regions. Conversely the UK has a higher deviation due to high dispersion of resource, coastline and grid connection.

7.5.5 Network Simplification

The work presented in the previous section demonstrated the techniques which have been applied to electrical market and grid topology data to reduce the complexity of the study area network. The NUTS regions were used to reduce the network to a bespoke grouping relative to coastal granularity. This method was explored by the author and presented in the conference [159]. Practical validations have been made for the grouping output based on the network system operator's defined (NSO) groupings. It was approximated that between 50 and 70 coastal nodes would be appropriate for allocation analysis. A final coastal grid connection nodal distribution was derived as, 23 (UK), 8 (IE), 6 (NO), 3 (DK), 3 (DE), 3 (NL), 2 (BE), 10 (FR), 7 (ES) and 5 (PT).

Figure 64 represents the coastal regional grid nodes and associated lines to which allocation was assigned.

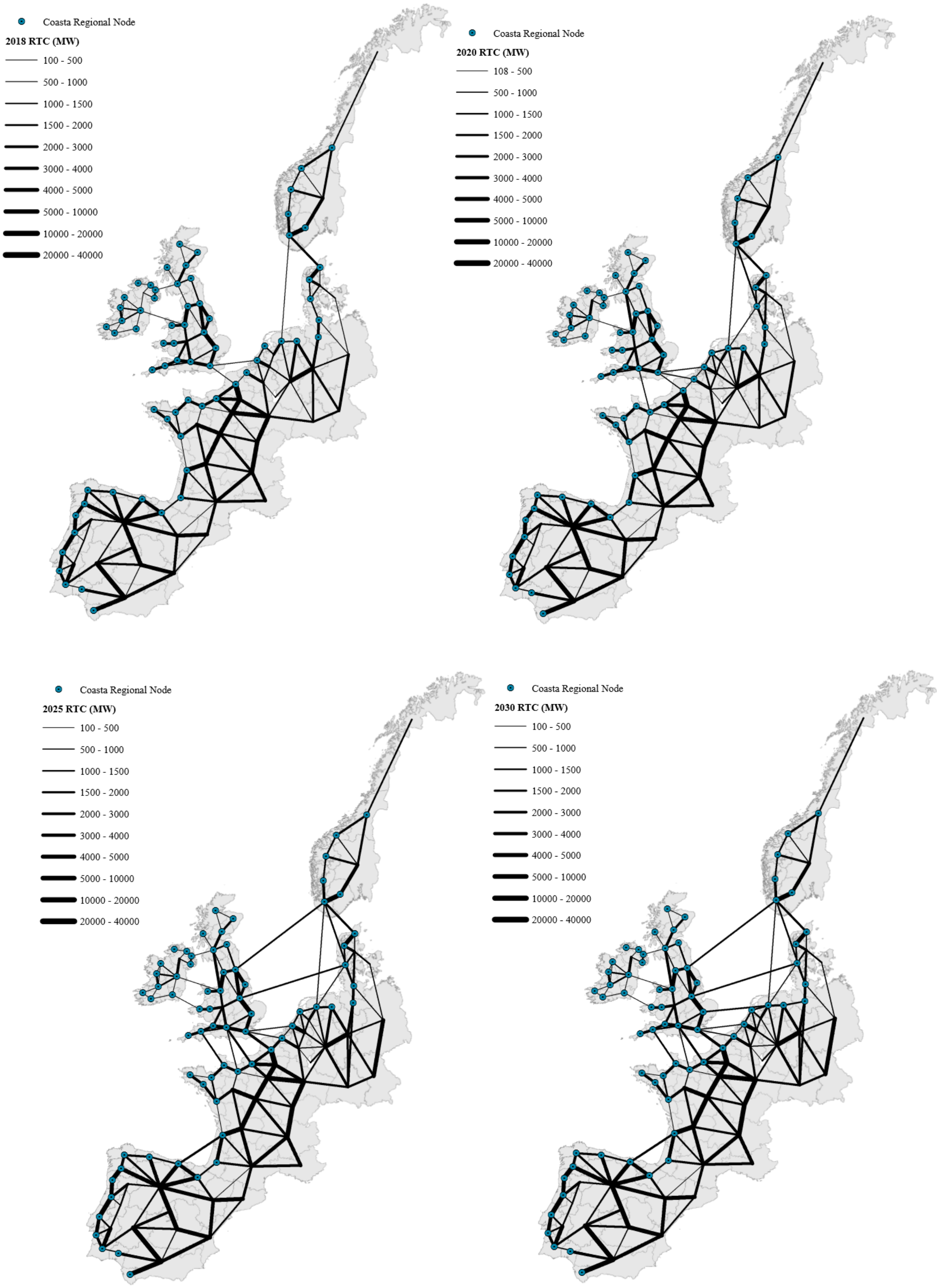


Figure 64. Network simplification for scenarios (clockwise from top left) 2018, 2020, 2025 and 2030 and coastal nodes where line thickness indicates transfer capacity.

The nodal transfer capacities demonstrated the local grid capabilities and how, in most study country cases, they were limited at coastal nodes. This was true for the cases of the UK, Ireland, Norway and France. However, the Iberian Peninsula of Spain and Portugal has a comparatively even distribution of connection capability at a coastal level.

The simplified system included the known changes set to occur over the forecast periods. The total transfer capacity in the system increased from 2018 as, 5% at 2020, 11% at 2025, and 12% at 2030. The significance of increasing the transfer capacity across Europe was such that key links may be strengthened, supporting increased levels of generation. The UK for example has 5 new interconnectors planned to 2025 to Europe and has a robust renewable project pipeline. The greater transfer across Europe was highlighted in the ability to connect to the wider system which could be more capable of absorbing increased generation and adding flexibility. A further aspect of grid suitability addressed in this work was the location of dispatchable power and demand. This was significant in the assessment of the volumes of connectable power to the grids ability to absorb variation in power production. When considering the mean annual distribution of the demand in the Western European, Figure 65, a variation can be seen between demand centres, dispatchable power and the coast.

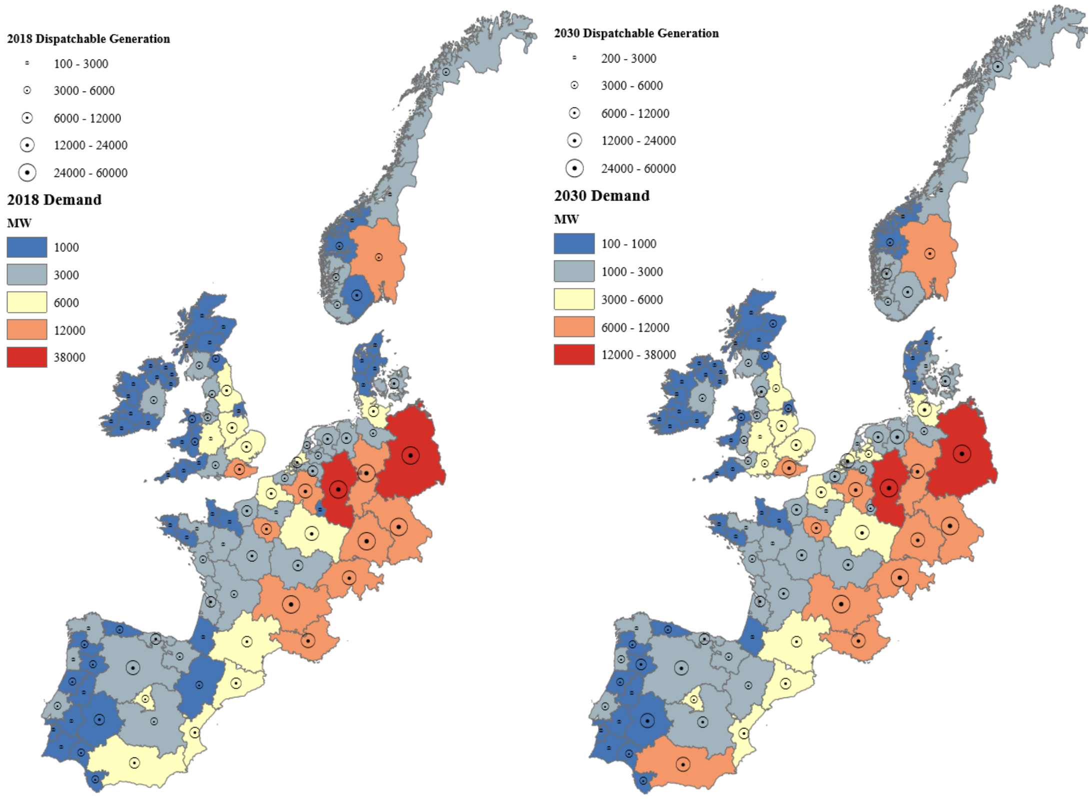


Figure 65. Reduced European energy system demonstrating the total aggregated dispatchable generation and demand for 2018 (left) and 2030 (Right).

What could be seen was that demand centres were typically located with high levels of dispatchable power generation. Also apparent was the lack of mean annual demand and dispatchable power at a coastal level. This indicated the model's sensitivity to power production variability and suitability of connection.

7.5.6 Theoretical Grid Capacity and Suitability

Two grid infrastructure characteristics were created from the generation, demand and network datasets. The first being, grid capacity and the second, grid suitability. The first a theoretical node hosting capacity, NHC, was estimated for each coastal node to which array cluster was connected. This value allowed for an approximation of connected development size to be established and at an estimated cost. Although an approximation a series of best assumptions was conducted to reflect the capacity available at each node. While it was known that other transmission and market constraints had an effect on grid capability, an initial target of 30% was set as the connection limit to reflect the assumed energy targets. However, this did not take into account the ability of the transmission network to export power to other larger demand centres.

As seen in Figure 64 and Figure 65 the regional transfer capacity (RTC) and demand were at their weakest on the fringes of the north Atlantic coast of Ireland and the UK. Therefore, an approximation was established to reflect the combination of both demand and transfer capacity. However, the simple addition of 50% of a regional demand and 50% of its RTC was highly unrepresentative of a local or national system. The UK and Ireland for example cannot consume or export the volume of power this metric would create and would therefore represent an unrealistic system. A proportional representation therefore was applied to reflect regions with low demand but adequate transfer capacity and the national demand. A 0-1 normalisation was fit to transfer capacity data with 10000MW and 100MW demand being the max min range. This factor resulted in larger regional demand using less transfer capacity.

The second allocation variable taken into account for the grid connection was the Grid Suitability Weighting, GSW. Weighting in this case was derived as the suitability of connection to a node. Where suitability was estimated as the local grid ability to deal with generation short fall. Both variables have been demonstrated in examples for 2018 in Figure 66 relative to the study area and connection nodes.

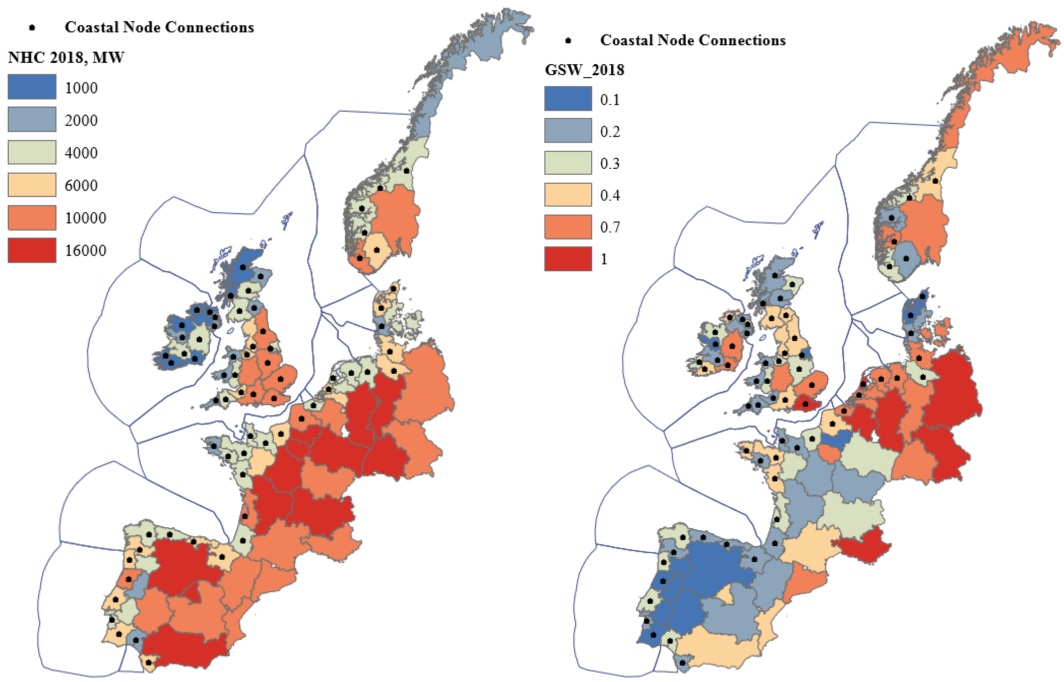


Figure 66. Mean annual node hosting capacity (left) and grid suitability weighting (right) with the coastal grid connection points. Red being the most connected

The distribution of nodes reflected the significance to the wave and wind resource outlined in the clustering model. Therefore, countries with increased coastline or higher resource potential carry increased coastal node counts. Countries with more grid nodes have increased connection possibilities, for example the UK with more than double that of any other country. Scotland, Ireland, Norway and Portugal had the most favourable distributions of LCOE. The relative NHC value was comparatively low compared to the interior regions of study countries. With the majority of the coastal regions having 1000 – 5000MW capability.

7.6 Port Connection

Port infrastructure as described in section 1.6.11 refers to the physical characteristics of a port or harbour. This includes the ability to handle the associated engineering plant and processes involved with constructing installing and maintaining developments. While energy flowing into a grid connection point was assumed to be a uniform product for both technologies, the physical specifications of the technology product vary a great deal. Unlike the grid connection dataset, the port connection points do not require reduction. Similarly, rather than creating an infrastructure data set, like with the grid connection, an existing port dataset was used. The world port index (WPI) has been used in similar work to determine suitability for the offshore industry, as seen in [92]. Therefore, to assess the capacity and suitability required for port infrastructure allocation the physical limits of technology was applied to the WPI dataset.

The WPI database was a geo spatial dataset of thousands of ports throughout the world with 32 characteristics of known facilities and available services. However, due to the nature of such global datasets they were not always as well recorded as was required for this work and in some cases underrepresented. Therefore, a desk top survey of the characteristics required was used to categorise ports and identify any missing data. Future upgrades or expansions were researched and added to the dataset for the forecasted time frames of 2020, 2025, 2030. The requirements of ports for the industry were known to be highly dependent on the types of operations and restrictions imposed. Port classifications must be tailored to the needs and abilities to form a specific roll for the technology. Within this work those rolls fell into two main categories, operations & maintenance (OM) and installation. The needs of the technology were highly variable and dependant on many, physical factors. Therefore, a dataset was established for both floating technology types. An initial spatial filtering was conducted in ARC GIS to only represent those relevant ports on the coastline of the study area**.** This yielded a potential 170 ports in the region suitable for analysis.

7.6.1 Operations and Maintenance

This work assumed that the nature of maintenance tasks did not require the removal of devices from sites to be repaired in harbour. Maintenance tasks were defined as those that can be performed at sea by crews or small repair teams in port. Therefore, the needs of floating wind maintenance were considered similar to that of the fixed wind industry and the characteristic requirements assumed similar. Requirements were assumed from [160]. Wave requirements were also considered similar due to the types of vessels associated with maintenance assumed from [97]. The two vessel types considered include crew transfer vehicles (CTV) or multipurpose vehicles (MPV) [53]. The characteristic requirements for both technology types was demonstrated in Table 10.

Table 10. OM port requirements for technology type. Where Ro-Ro refers to the roll off roll on delivery capability to receive goods.

Characteristic	Wind	Wave
Vessel width (m)	20	20
Manoeuvrability (m)	40	40
Clearance (m)	50	50
Quay Depth (m)	5	5
Channel Depth (m)	3.5	3.5
Quay length	80	50
Storage Area (ha)	2	0.2
Quay Area (ha)	2	0.1
Quay Strength	Y	Y
Handling	Y	Y
Heavy Cranes	Y	Y
Fabrication Facilities	Y	Y
Ro-Ro	Y	Y
Road/Rail Access	Y	Y

Although understood to be similar the key difference between the two technology types were the type of repairs to be carried out. Wind maintenance could include the larger MPV needed multiple large components such as gear boxes and/or blades. These components require onsite large heavy lifting equipment as well as adequate storage space. While the components that could be repaired in situ on the wave converter were considered to be more manageable and smaller requiring far less. Minimum requirements for operations and maintenance ports filtered the port dataset to 120 locations.

7.6.2 Installation

Aside from the mooring and cabling laying activities, installation of the technology refers to the prefabricated components assembly and load out of devices to site. The floating wind spar buoy technology consists of two key components, they include in the ballast section of spar and the turbine tower. Figure 67 demonstrates the assumed process to compete the load out process to site.

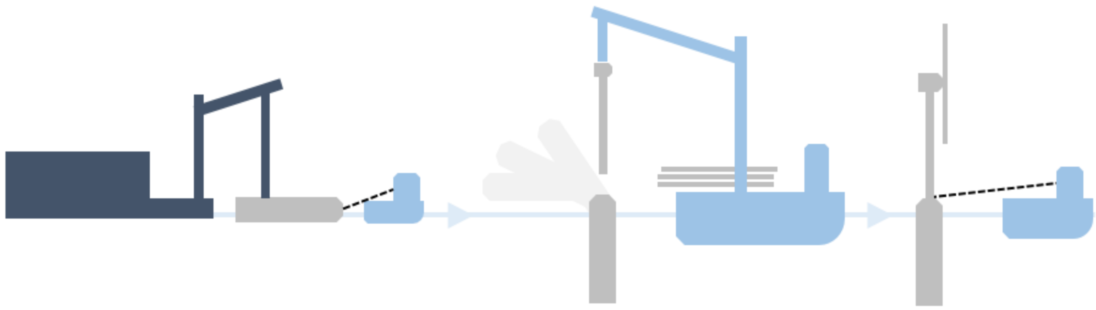


Figure 67. Floating wind installation two stage process from port to wet assembly and to site.

A similar process was used to install the technology at the Hywind array in Scotland [161] where device were assembled in deep water in Norway and through the North Sea. Due to the 70m of the ballast section requiring heaving lifting and manoeuvring on the quay side, considerable quay and port facilities were required. Furthermore, to manoeuvre and perform wet assembly the port must be extremely sheltered and have ample room for vessel activity. The wave energy converter had a different assumed load out installation procedure. However, as this technology was still in development little was understood about mass installation. Although requiring similar technical and handling ability, the extremes in requirements were lower due to the smaller size of the devices, 10m diameter 15m draught. However, the process still required either the towing or out to sea directly or a transitionally barge to deeper water, as depicted in Figure 68.

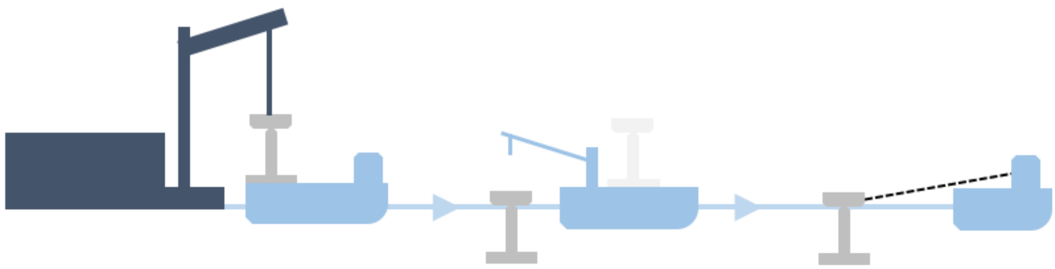


Figure 68. Floating wave installation two stage process from port and barge to site.

An overview of the requirements of both industries were established from [53]. While more detailed port requirements assumed from [97] for wave energy and wind characteristic requirements from [162] and the key spar buoy limitations addressed in [18] and defined in [160]. The characteristics required for such operations determined the suitability of a port. This has been presented in Table 11 for both technologies as a basic requirement.

Table 11. Installation port requirements assumptions.

Characteristic	Wind	Wave
Vessel width (m)	45	45
Support Tug	Y	Y
Manoeuvrability (m)	200	100
Clearance (m)	110	50
Quay Depth (m)	9	7
Channel Depth (m)	9	5
Quay length	150	80
Storage Area (ha)	5	2
Quay Area (ha)	3	1
Quay Strength	Y	Y
Heavy lift	Y	Y
Fabrication Facilities	Y	Y
Ro-Ro	Y	Y
Road/Rail Access	Y	Y

Clearance and manoeuvrability required for floating wind was directly relative to the size of the component being manipulated. Quay strength, depth and length were also dominated by the component assembly process and therefore were larger for wind. Heavy lift cranes in port were assumed to be similar due to the nature of offshore wind operations utilising in many cases dockside, floating barge or purpose installation vessel cranes. Similarities between technologies were seen for the requirements in access and onsite fabrication capabilities. Quay area varies dependent on technology type. However, in this case the assumed space was considered greater for wind. These characteristics were considered to influence the capability of a port to handle varying numbers of devices per year. Minimum requirements for installation ports filtered the dataset to 68 for wave and wind 52.

Table 12. Port size requirements varying load out scenarios.

	Wind		Wave	
Characteristic	S2	S3	S2	S3
Vessel width (m)	45	45	45	45
Manoeuvrability (m)	200	400	100	200
Clearance (m)	110	110	50	50
Quay Depth (m)	9	9	7	7
Channel Depth (m)	9	9	7	7
Quay length	150	300	70	150
Storage Area (ha)	20	50	5	10
Quay Area (ha)	6	6	2	2
Dry-dock (m)	200	200	100	100

7.6.3 Suitability Ranking

The suitability of ports was reflected by the requirements of each technology. Work in [92] demonstrated the needs in the wind industry for load out and maintenance operations in order of industry requirement. The considerations have been used to develop a similar ranking order, Table 13 and Table 14 used to filer the ports in preference with a tailored focus to the two technologies.

Table 13. Installation port suitability ranking for both technology types and their contributing attributes.

Ranking	Wave	Wind
1	Quay Strength	Quay Strength
2	Port's depth	Manoeuvrability
3	Quay length	Port's depth
4	Storage area	Quay length
5	Handling	Quay area
6	Road/Rail Access	Handling
7	fabrication facility	Road/Rail Access
8	Quay Area	fabrication facility
9	Manoeuvrability	Storage area
10	Ro-Ro capability	Ro-Ro capability

Table 14. Operations and maintenance port suitability ranking for both technology types and their contributing attributes.

Ranking	Wind/Wave
1	Quay Strength
2	Fabrication Facilities
3	Road/Rail Access
4	Handling
5	Quay length
6	Quay area
7	Heavy cranes
8	Port's depth
9	Manoeuvrability
10	Ro-Ro capability
11	Storage area
12	Storage load bearing capacity

7.6.4 Theoretical Port Capacity and Suitability

A quantifiable volume of 'capacity' was established for the port infrastructure dataset used in allocation modelling. Capacity was defined as the ability to service or build out a certain number of devices to one or multiple sites and was built around installation ports at a single time. This approximation did not consider the staggered approach but rather the maximum coverage of infrastructure for the maximum number of arrays at a given time frame. Both technologies and their specific requirements were categorised in terms of ability to handle a certain number of devices per project, where a project was defined as taking approximately 2 years of port activity during installation. Installation ports were therefore defined in three categories, S1, S2 and S3, each with increasing levels of capacity.

As seen in [53] ports in these categories can handle a load out from 100, 300, 600 wind devices per year. However, due to the size and manoeuvrability required for the spar buoy design the requirements for port configuration can differ. Similar can be said for the wave energy device whose design required less quayside handling and could feature a larger per year load out rate. Figure 69 demonstrates the assumed characteristics that could influence the load out conditions used in this work.

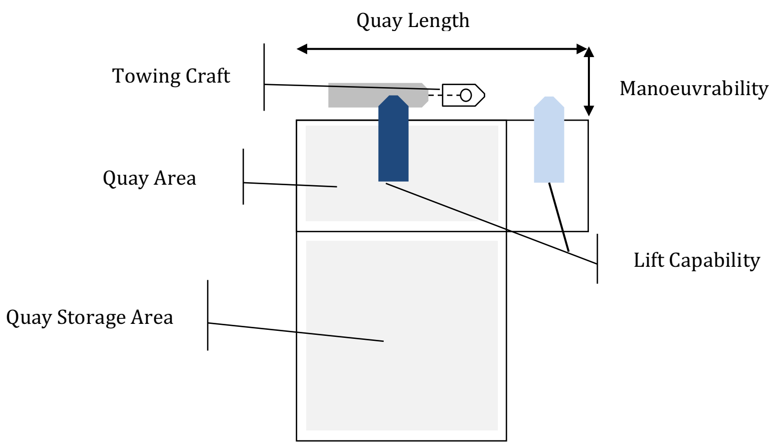


Figure 69. Floating wind example port configuration requirement assumptions.

A large theoretical hosting capacity, load out rate, was dependent on the ports ability to handle multiple devices. An S1 port having an annual load out of 200 wave devices per year or 100 floating wind turbines. These ports capacities effectively doubles with the port factors set and creates capacity values for S2 and S3 ports of 400/600 and 200/300 devices for wave and floating wind respectively, similar rates were observed in [53]. The load out rate was applied in the allocation modelling as the theoretical capacity to be explored in the modelling work. Figure 70 illustrates the distribution of categorised ports across the study area used in the analysis.

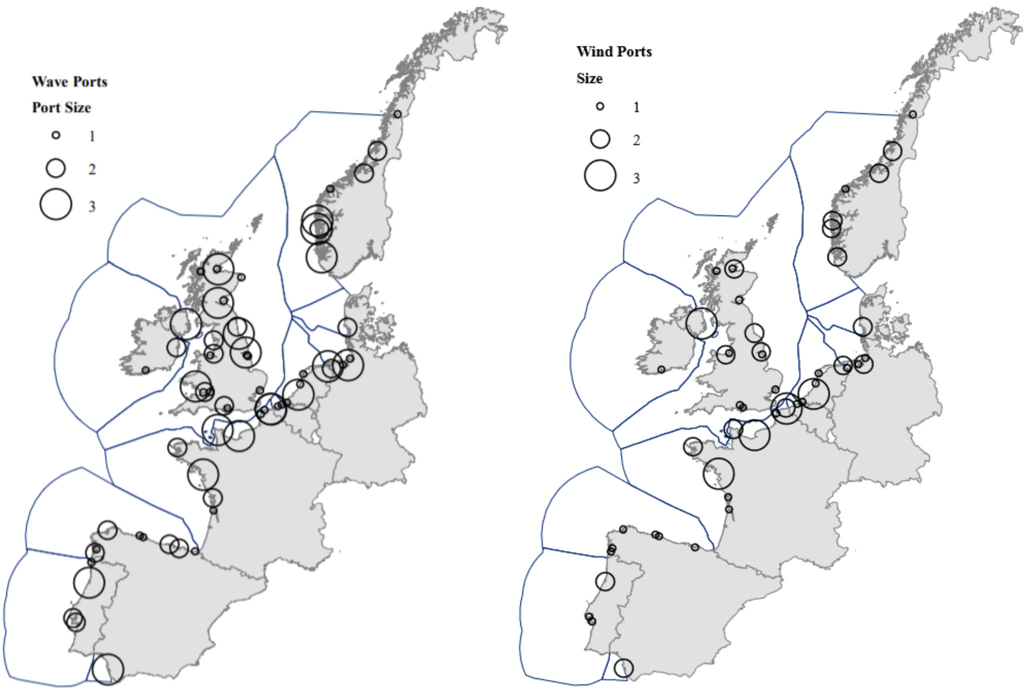


Figure 70. Port size categories for load out sizes in 2018. Of the total 170 ports originally in the database a remaining 68 and 59 for wave and wind respectively were identified as suitable for analysis.

Although these values were specific to these technologies, they were representative of other similar technologies in both sectors. Understood to have a large impact on the port's locational suitability, depth outside of port was crucial to the spar buoys floating installation. While installation techniques differ from device to device the requirement for deep calm water to couple turbine to sub structure determined that only coastal ports with depth greater than 70m were suitable. This demonstrates a reduction in port suitability for this technology type with a loss from 59 suitable ports to the utilised 26. However, installation techniques may progress to in situ installation and other floating concepts already can be towed at shallower depths. What can be seen in the 2018 distributions was a general increase in both capability and number of ports for wave energy. This limited suitability of ports in Western Europe for floating wind operations was observed as in [104]. The table in appendix 12.6.1 demonstrates the upgrades that were poised to occur within the time frames assessed. Several countries have identified the need to improve ports for floating wind technology and were tailoring infrastructure to these needs. The ports of Brest (North West France) and kishorn (North West Scotland) were two such developments that were underway for the floating wind sector.

It was known that distance to site had a large impact on suitability. It was observed in the industry assessment into wind development requirements to be the most significant factor in infrastructure suitability [92]. Therefore, within the allocation model an impedance value skews suitability to favour the closest option first. Suitability was estimated by the favourability of the ranked port characteristics relevant to the technology. Similar to the grid connections the planned port upgrades to support already being developed the industry these were also included in the assessment. Operations and maintenance (OM) rolls were estimated in this work through the type of craft suited for operations. While it was known that maintenance differs between the technologies it has been assumed that small scale operations were comparable and therefore use comparable port limitations. While larger operations of maintenance of both technologies were conducted in port after uncoupling and towing of the device. The resulting suitability estimations for operations and maintenance have been presented in Figure 71.

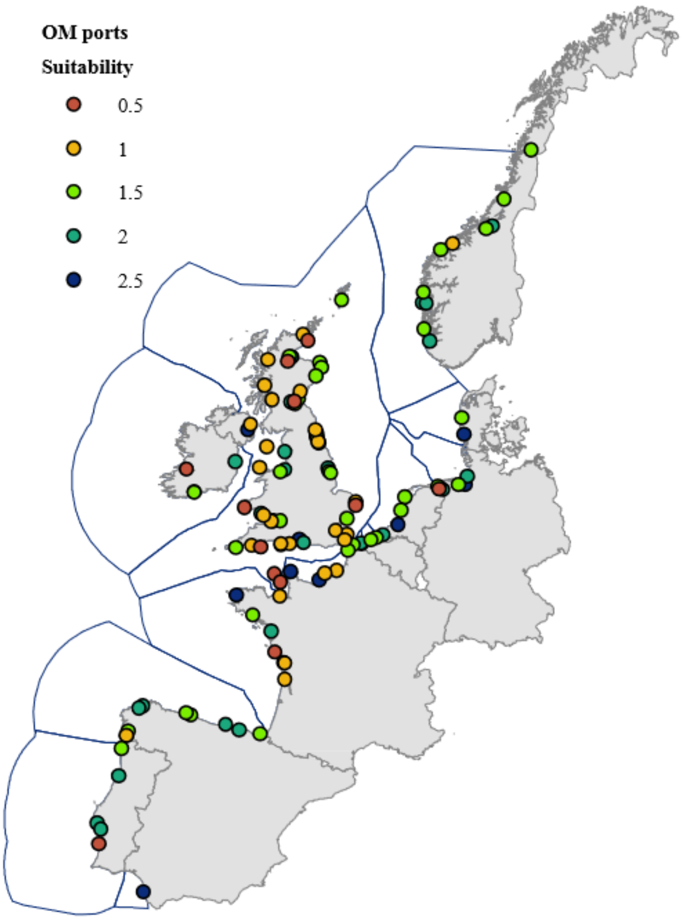


Figure 71. Operations and maintenance port suitability rating for both technologies for 2018. Of the original 170 ports 120 where identified as suitable for the industry.

The distributions of operations and maintenance ports for both technologies show a broad distribution around the study country coastline. The majority of ports falling in the category of middle or high suitability, with only 12 being at the bottom 10% of suitability. The most suitable port locations were seen in regions where increased heavy offshore operations have traditionally been seen, this was apparent for the North Sea, coast of Norway and northern Spain. While the North West coast of Ireland and Scotland had relatively poor scoring OM ports.

7.7 Allocation Modelling

The solver tool in ARC GIS, *location allocation* can be used to identify volume-based connections for multiple demand points restricted to a network pathway. It iterates through all possible combinations to find an approximate optimal, or heuristic, distribution across all locations under constraints. The solver starts by creating shortest-path costs matrix between all the facilities and demand point locations in the network. The algorithm performs a process known as Hillsman editing which enables the same overall heuristic solver to work through a variety of different problems. The number of solutions possible in such a problem can increase rapidly, which drastically increases the computational complexity. A problem of 100 facilities with 50 locations yields a potential n solution count of 1x10^30. As this work examined tens of thousands of points, the problem of non-heuristic approaches was obvious. After cost path editing a set of semi random solutions is generated and substitution heuristic, Teitz and Bart, is applied to refine solutions to create a group of desired solutions. A metaheuristic iterates and refines the solutions until no additional improvement is possible, at which point the best solution found and could be considered near-optimal.

Figure 72 demonstrates the process involved to fulfil both infrastructure variable allocations. First, to distribute the power produced at each array cluster to a grid connection. Second to allocate the number of devices to a suitable port for installation and maintenance operations. Case study scenarios have been established to estimate the theoretical allocation volume to both infrastructure types**.** However, within this section an example output for the UK has been presented due to its relative port and grid capabilities and potential seen in section 6.3.

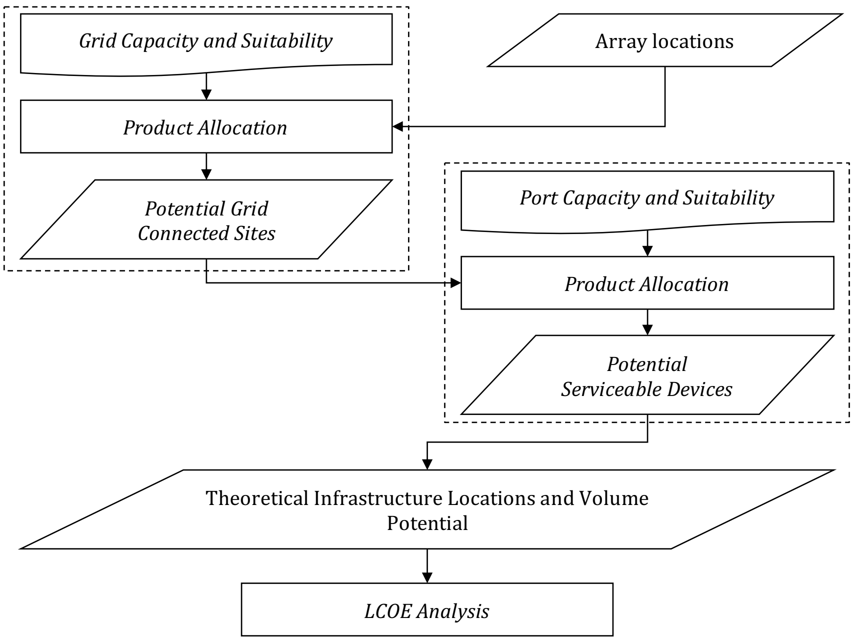


Figure 72 - Spatial Analytical Processes in *Infrastructure Allocation* Modelling with two main sub models (in dashed boxes).

This process sought to solve one model, grid connection and port connection, at a time. This process was established due to the relatively more demanding challenges of grid connection compared to port logistics. Therefore, the model outlined, allocated possible sites to the grid connection nodes and those selected sites were then allocated a suitable port. This process output a volume of connected and serviced arrays as well as the distance of connection, used to determine LCOE. This novel method provided a solution to the question onto the relationship of capacity and capability. Both technology types and all forecasts were simulated for each country in the study area as well as the case studies outlined in section 2.5.3. This study assumed that the development takes place at a stage of commercial technology readiness and forecasts were developed to demonstrate the changes to current roll out potential and therefore not a cumulative assessment.

7.7.1 Maximised Capacity Coverage

The maximum capacity coverage algorithm, illustrated in Figure 73, distributed the maximum volume of demand points, arrays, to capacity limited 'facilities'. The function distributed the optimal grouping of arrays to satisfy the capacity without exceeding limits under an impedance constraint. The location of port facilities was known and fixed at actual locations. However, grid nodes represented the aggregated location of the high voltage transmission system within a region. The regional node represented the most significant grouping of internal transmission connections and was therefore an approximated location.

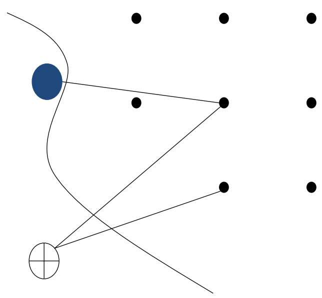


Figure 73 – Spatial demand allocation link of offshore cell matrix to both facility types blue dot (port) cross (grid).

The algorithm located the maximum number of arrays rated capacity MW with the lowest impedance, distance, value. Due to the number of arrays being located a ceiling function was applied to each wind MW rating to the nearest 100MW. To ensure that the most attractive sites were chosen the preliminary unconstrained LCOE values from section 6.3. were excluded from analysis. Those sites being those falling outside a £130/MWh (wave) and £110MWh (wind) price by 2030. As previously discussed within this work £100/MWh would be considered a cost competitive LCOE. However, this has been increased to reflect the LCOE sensitivities, section 6.3.3 of approximately £30/MWh and £10/MWh for wave and wind respectively.

A cut off length in this case was set to 400km for grid connectivity while port impedance limits were capped at 600km which represents the ability to transport devices to a site from port. Although known to have impacts on modelling it fell beyond the scope of work to assess the impact of this cut off length. Although restrictive this represents a technology advancement in cable length by over three times the current commercially utilised length. In both cases the nearest site was favoured in the allocation objective function. The impedance function set in this model was chosen to be linear. This means that the solution facility was the sum of distances to arrays. Although this analysis used estimations that were best approximated the output of the allocation modelling was restricted to representing a solution to these inputs.

7.7.2 LCOE Estimation

Cost estimations were established using the same method and non-distance-based variables seen in section 6.2.1. The distance variables that drive LCOE were taken as the distance to installation port and transmission grid. Further the distance to suitable operations and maintenance facilities was introduced. A closest facility tool in GIS was applied to assign the distance to OM locations. With these three variables of distance to, installation port, grid and OM port, the LCOE model was run. This reflected a change from the unconstrained LCOE to the new infrastructure capability constrained LCOE.

7.7.3 Directional Loss

Directional power loss functions discussed in section 4.6.3 were applied here. Performance was impacted by the wake of prevailing arrays indirection resource and this impact compounds depending on the number of arrays as depicted in Figure 74.

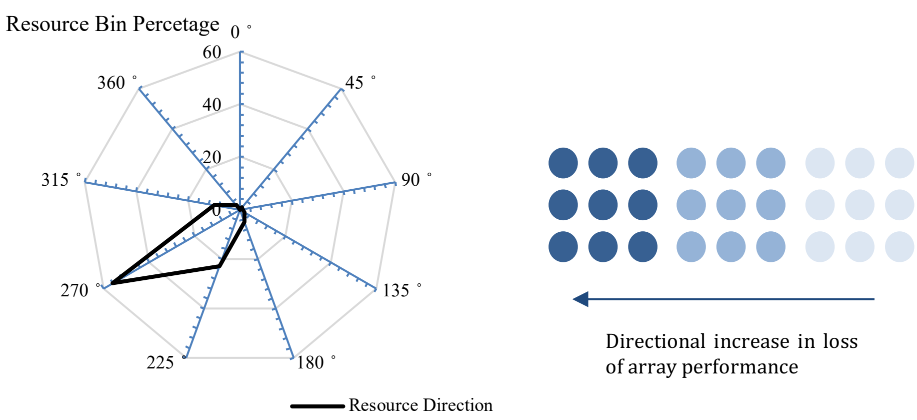


Figure 74. Directional wake loss example and resource rose plot with resource bin percentages.

As depicted in figure above the directional inter array wake loss increases with the number of arrays according to direction. Array power loss estimates were highly dependent on spacing and technology assumptions and this work could be expanded as described in section 10.1.1. The bin percentage was used as a weighting factor to determine the strength of the directional component. Power loss ranged from 1-5% for wave arrays of 1-4 groups deep and 2-7% for similar sized wind arrays. The result of this loss in performance was a reduction in overall power out and therefore an increased LCOE estimation.

7.7.4 Capacity Coverage Model Assessment

As outlined in 7.2 the allocation process runs to solve one infrastructure distribution simulation prior to another. Figure 75 illustrates the allocation process and the variation in array to infrastructure distribution based on the grid and port connections separately.

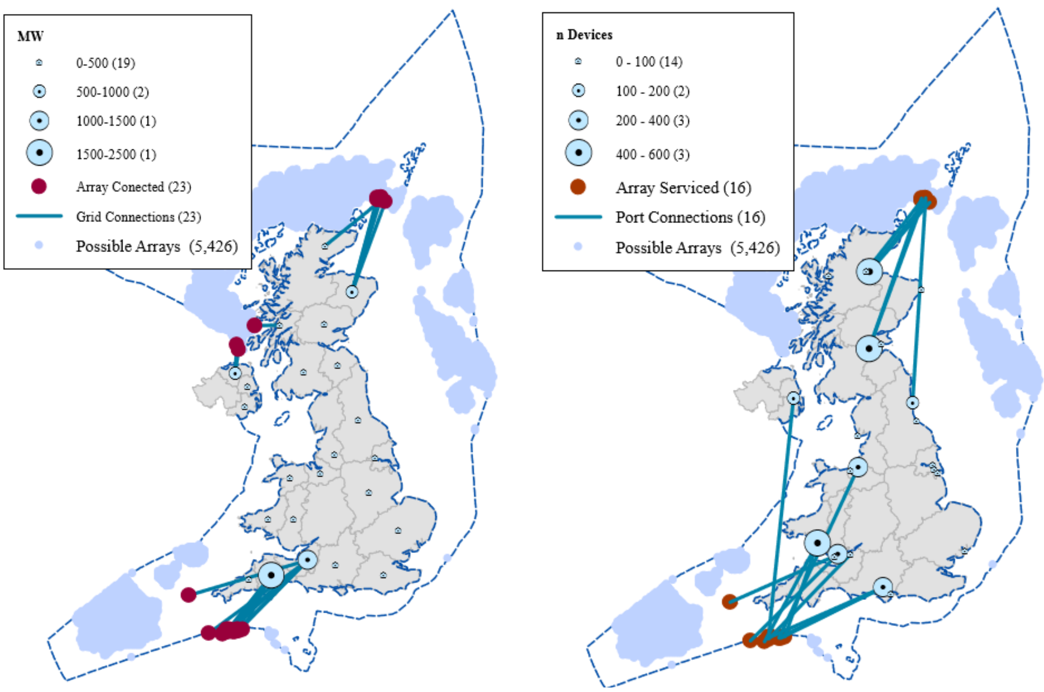


Figure 75. Allocation process, intermediate model outputs or grid (left) and ports (right) with assigned volumes of power and devices.

The initial stage of the model, grid allocation, demonstrated the selection process from the possible arrays and highlights, where and how many, arrays could be connected. The secondary stage, port allocation, sought to service these sites to ports. The staggered load out in this work was considered to be the total load out possible in a two year development period for each forecast. In this case 23 arrays could be grid connected, whereas 16 arrays could be serviced due to port limitations. This highlighted the relative weakness of port facilities to meet grid capacity potential. Within the allocation modelling process several weaknesses were observed and known to have an impact on site selection. The first being the models overriding objective to snap to the nearest array location rather than seek a combination of distance and array potential. Although this has been reduced through the selection of high performing sites from previous modelling work, it was observed to have an effect. Further the model seeks to fulfil the largest array quantity within the capacity of a facility but does not allow for the sharing of array volumes to be met by multiple infrastructure connections or partially by smaller connections. Impedance, distance, values were dependent on the cost path matrix established along the offshore network. This network does not take into account small geographical or bathymetric entities that could be avoided or cabled over, such as islands. Due to this reason, several small islands creating a more expensive cost route around them. However, this has been explored in part as further work in section 10. Although this analysis used estimations that were best approximated therefore the output of the allocation modelling was restricted to representing a solution of these inputs.

7.7.5 Spatial Distribution

The combination of the modelling techniques applied created a new LCOE value based on the new distance variables to grid and port infrastructure. An example output of the allocation modelling process and its impact on the LCOE for wave energy was demonstrated in the following figure.

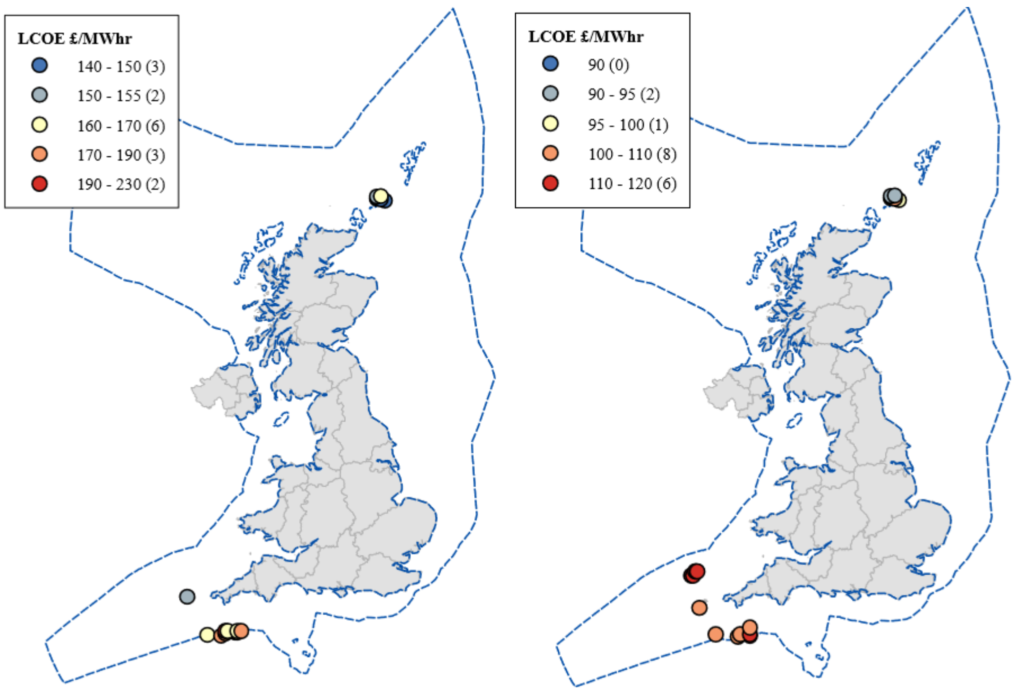


Figure 76. UK LCOE of grid and port allocated Wave arrays, for two forecasts 2018 (left) and 2030 (right)

While comparing the two outputs it can be observed that the cost of connection decreased over time. What was also apparent was the increase in array connections for certain areas. However, over time limited increases in installed volume were seen. The UK was selected as an example due to the number of key features which make it unique to the industry. The country has, as has been discussed throughout this work, high resource potential and high infrastructure suitability. However, it was also unevenly balanced in terms of distribution while the bulk of demand, transfer capability and port capacity were located away from the best quality resource. In this case the model was run independently from other study countries. In practice port operations are more dynamic spanning multiple sites over multiple countries. Port logistics can be more flexible and take on multiple configurations whereas the need to connect to the grid was inherent to national energy supply. An example of installation logistical operations meeting the requirements of a floating site were present in the Hywind demonstration park [161]. Here a Scottish grid connected array was constructed and towed to site from ports in Norway. Therefore, for all simulations a 'dynamic port connection' was assumed within the distance parameters of 800km to represent operations for installation occurring in multiple countries, while being connected to the country or countries being simulated.

7.7.6 Variable Sensitivity

Within the allocation modelling process several key variables were noticed to have a significant impact on the outcome. Three variables were selected for sensitivity analysis, those being, and impedance limit for grid connectivity, port capacity and grid capacity. A sensitivity analysis was conducted into each input to determine its effect, the results of which were presented in Figure 77. The percentage increase was chosen to represent the potential approximation error for both ports and grid. For ports misrepresentation of 25% could be attributed to the sizing and internal logistics affecting the capacity. For the grid 25% increments also represented the significant change in capacity estimates based on demand and transfer capability. The same was applied to the impedance cable length which represented changes from 400km. This was approximated due to the relative increments found in offshore wind cabling ranging from less than 50km to over 200km.

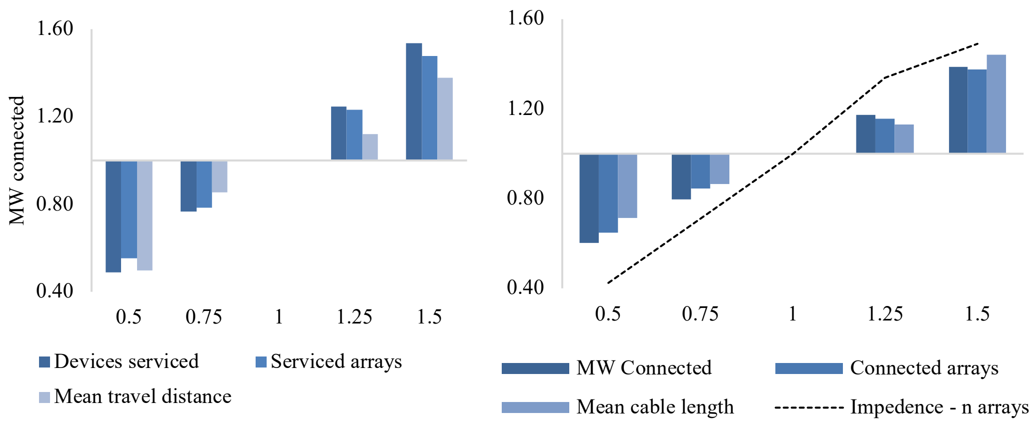


Figure 77. Key variable sensitivity analysis for grid infrastructure (left) and port (right).

What was observed both plots and each criterion was the linear trend with magnitude. The grid capacity and port demonstrate a direct link to capacity connected and devices serviced. The mean cable length and travel time however did vary. This variation away from the normal trend was due to the spatial distribution of capacity and its significance to location of sites. The impedance cap limited the number of arrays due to the length of the suitable cost path being reduced. However, it curtailed at larger lengths demonstrating that the progression from shorter 100–300km lengths was more limiting than those longer than 400km, therefore 400km impedances were assumed to be most suitable. What was apparent from this analysis was that the capacity from both infrastructure types had a clear linear impact on the results. To further improve the understanding of the suitability of infrastructure, further analysis was established to examine these sensitivities.

7.8 Grid Analysis

Further analysis was conducted to explore the relative sensitivities for grid connections. The allocation of array power output to coastal grid connection nodes was subject to a number of constraints seen in a wider grid system not applied in the allocation modelling which sought to include demand and transfer capacity capabilities. As observed in literature two factors were considered to be most significant in terms of renewable penetration into the energy mix. They include, security of supply through reduced generation variability and the cost of generation. As was outlined in section 7.4 the nodes within the countries being assessed in this thesis were assigned generation, transfer capability and demand data. This work considers the optimal energy mix solution subject to these factors for the Western European system. A genetic algorithm numerical solver tool in excel was applied to solve the optimal mix of energy for the penetration of new floating WWE in the system for each of the scenarios assessed in this thesis.

7.8.1 Cost of Generation

Within the mix problem, cost, C_g, was defined as an amalgamation of the cost of energy per type and the cost of carbon and was defined as the following:

$$C_g = (\text{MWh cost}) + (\frac{CO_{2\,\text{factor}} * CO_{2\,\text{price}}}{\text{Efficieny}})$$

Equation 22

The carbon price applied was established through the trending EU energy targets for carbon-based generation. It demonstrated for the carbon-based technology in Table 15. Approximations being an estimate from an amalgamation of values from ENTSOE data and data from [89] [163] [164]. The values considered the development of technology and the fluctuation in efficiency, η, as well as the carbon factor by energy type and the associated cost per MWh Table 16.

Table 15. Carbon pricing approximations.

Year	2017	2020	2025	2030
CO_2 price (£/ton)	18	25.7	54	62

Table 16. Generation type variables, with efficiency, η. Where the cost of energy was an assumed high mean and low from [89] [165] [166] European representative values converted at a rate of, £ 1 = € 1.13 = $ 1.26

			Cost of Energy £/MWh		
Type	η	Carbon Factor CO_2/MWh	high	mean	low
Coal	0.4	0.27	90	70	60
Gas	0.49	0.16	80	70	60
Nuclear	0.33	0.01	100	90	80
Oil	0.36	0.22	180	140	100
Bio Fuel	0.3	0.01	120	100	80
Other Non	0.35	0.22	160	130	100
Hydro	na	na	100	70	40
Solar	na	na	90	70	50
Onshore wind	na	na	90	70	50
Offshore wind	na	na	160	120	80

Naturally assessing the cost of energy for each fuel type across the study countries contains a degree of inaccuracy. This was represented by the high and low values for cost per MWh. Further, forecasting C_g based on carbon price across to 2030 was problematic due to changing political landscapes. However, it has been assumed in this thesis that carbon prices will be met across each of the study countries. Table 17 represents the inputs in the energy mix model across each of the forecasted scenarios.

Table 17. Estimated 'cost 'of generation, C_g, over scenario forecasts for generation types and groups of, fossil fuels, renewable energy and floating renewables. While floating prices were extracted from the allocation modelling work for each node.

Type	2018	2020	2025	2030
Coal	77	82	87	127
Gas	73	76	78	97
Nuclear	90	91	91	93
Other Non RES	146	151	155	191
Oil	137	141	146	184
Biofuel	100	95	90	70
Hydro	60	60	60	60
Solar	65	60	55	50
Offshore wind	120	100	80	60
Onshore wind	75	72	65	60
Floating wave	…	…	…	…
Floating wind	…	…	…	…

Variability in fuel prices, owing to the volatile nature of such markets, was factored into the forecasts made by the ENTSOE through a series of development case studies [167]. It was considered in this work that nuclear fuel prices were to remain relatively constant in comparison to other fuel prices. Furthermore, it was also assumed that renewable sources do not have a cost of carbon and therefore cost of generations based on the cost per MWh. Although the cost of renewables varies dependant on the site, study wide mean values were used with the sensitivity of this assumption represented in results section 8.4.1. The difference between fossil fuels and the renewable sources was the change in cost over time. Where cost reductions were factored in to 2030 as renewables become more developed. Conversely the cost of generation increase over time for fossil fuels was dependent on the carbon cost and efficiency of the generation type. It was assumed that minimal improvements will be seen in generator efficiency and that the driving factor for fossil fuel cost will be the cost of carbon.

7.8.2 Temporal Variation

As discussed in section 4.7.2 on variability energy production from arrays can vary over time. This variation was also seen in the geographical scope of the work with power output of arrays changing depending on location. To address this variation the solver, to be described in the following section was performed on each of the time frames chosen for power production measurement. These include the seasonal time frames of summer and winter, measured from the three seasonal months of June - August and December - February. Whereas the diurnal time frames were measured over six-hour time periods for day and night at 3-9 pm and 12-6 am.

Generation types were divided into two categories, dispatchable plant and non-dispatchable plant. Dispatchable units were defined as generation types which can adjust power production to ensure a network balancing subject to the limits of their availability as well as the minimum stable generation seen in Table 18.

Table 18. Generation characteristics for fuel types. It was understood that availability factors range across technology types considered the following factors have been established. The data included in this table represents annual outages and shut down times. A mean value from, ENTSOE TYDP and [89] was established.

Gen Type	Availability, %	Min stable generation, %
Nuclear	80	50
Coal	75	43
Gas	90	34
Oil	76	35
Mixed Fuels	60	35
Biofuels	90	34
Other RES	80	20
Hydro	60	20

Non-dispatchable units were defined as non-adjustable generation types that due to technical and economic reasons cannot vary power production to ensure a network balance. This was accepted as the variable nature of renewable resources and therefore affect the wind and solar input generation values. Availability values for wind and solar vary geographically. Establishing generic availability factors across technologies and locations was inherently problematic. Not only due to the paradoxical issue of location-based resource characteristics driving performance. However, generalised mean capacity factors from industry reports were assumed for all locations as with a percentage error: 0.45% (+-10%) offshore wind, 0.30% (+-5%) onshore wind and 0.25% (+-5%) solar. Temporal variation for these energy sources was factored into the model to represent the renewable variability already existing in the energy mix. Fixed offshore wind variation was assumed from resource modelling conducted in this work in section 4.7.

The temporal resource variability difference from the mean for each time frame was used to create a resource ratio which scales the capacity factor. This created a temporally scaled capacity output for renewable generation. A similar scaling method was applied to demand data from the national statistics used throughout this work. The solver modelling constraint of a fixed maximum number of variables leads inputs to be limited to ensure computational suitability. The generation data was grouped into 3 energy types to simplify the problem. The three types include, floating wave and wind energy (WWE), renewable generation (REN) and dispatchable fossil generation (DISP). Hydro power and biofuels were included into renewable generation although they could be considered dispatchable energy sources. Offshore wind resource data was assumed from the resource assessments established in this thesis in section 4.7. Demand variability for each country was applied to the nodal distributions identified in section 7.5.1. Variability data was established for the temporal bins used in this study with historic statistics data from [81].

7.8.3 Genetic Solver Method

In order to conduct assessment into the optimal energy mix for each country, a numerical solver was applied. The model created in Excel applies the genetic algorithmic (GA) technique of evolutionary solver principles. This was selected due to the problem being assessed having non smooth mathematical properties and containing unknowns required for analysis [168]. The optimisation algorithm applies associated evolutionary principles found in natural selection to find the 'fittest' or 'best' individuals in a population. These best solutions will be the 'best' values to satisfy the objective function within constraints. This worked on a metaheuristic fashion to start with randomised 'population' input values. Within each level of iteration, a best performing individual was chosen to generate new individuals through either mutation or crossover between 'parents'. The Excel GA solver employs multiple methods to carry out both crossover and mutation. Figure 78 demonstrates the generalised process iterated through generations to acquire a 'best' solution.

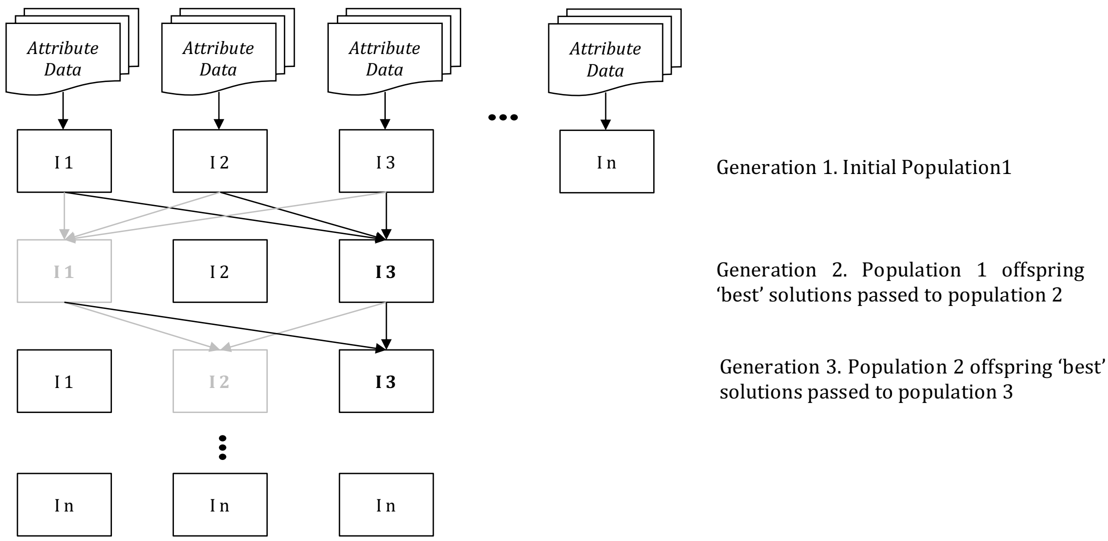


Figure 78. Evolutionary solver process of best solutions for both mutations (black) and cross over solutions (grey) between individuals, *I n*. The process was iterated until an optimal or close to optimal solution was identified.

The final stage of the solver was to choose which of the solutions was best in total number of outcomes. The solver applies a minimum, maximum and best fit of values to achieve the objective function yet stay within the constraints set. In this process there were several GA solver parameters that were required to ensure that the solver was indeed producing best fit solutions.

- *Convergence,* being the maximum percentage difference between objective values of the population, once within this limit solutions were considered suitable.

- *Mutation rates*, the frequency in which a member of a population will be altered to create a new solution during each generation (also known as sub problem).

- *Random seeding,* referring to the random selection of the initial population of individuals.

- *Time without improvements,* a time-based variable set to stop iterating through generations when solution convergence does change by the specified amount.

- *Bounds of operation,* meaning the solver will only run between the limits of positive integer constraints and therefore increase the focussing of solutions between the set values.

The population in this case referred to variables involved for the allocation capacity to satisfy model constraints. The solver progresses through stages of population distribution with the best solution 'offspring' attributes being passed down the 'genetic' line to provide a mutated outcome of best values. The objective function was to solve the energy mix to meet demand but to utilise generation units under the lowest system cost as defined by the following equation.

$$\min\left(\mathrm{C}_g\right) \mathrm{G}_c \sum_{\mathrm{gN}} \mathrm{G}_c \mathrm{Pg}$$

Equation 23

Where cost, C_g, was minimised over the sum of the associated costs for the capacity of generation available, *Pg,* for each generator group of WWE, DISP and REN. Within this model this objective function was subject to a number of constrains which were nodal and system wide:

- The energy generation at a node could not be larger than the combination of demand and transfer capacity.

- The model could not reduce the generation capability of renewable generation already existing at nodes.

- The only adjustable variables were the nodal dispatchable plant and new floating WWE. While dispatchable plant could not be reduced to lower than the mean stable generation for the plants grouped.

- A minimum renewable energy mix of 30% must be achieved for the total system generation.

- Generation cannot exceed demand by more than 2% of the total.

In order to represent the European network system and energy market in relation to floating WWE it was identified that the system should be modelled as in one numerical optimisation. However, due to modelling limitations identified in Excel the number of individual node variables exceeds computational viability. Therefore, the energy system was treated as an isolated 'island' grid network to reduce variable count. 103 nodal points were identified across the study area countries. The Iberian Peninsula was considered to be relatively isolated from the European transmission network, as identified in the literature seen in 1.6.7. This means that bordering nodes of France and Spain utilised this boundary as a slack node where energy can be freely exported across the existing interconnector capacity. This resulted in 81 nodes remaining in the larger European system and 23 in the Iberian system. This simplification was understood to contain a degree of uncertainty; however, it was identified that the interconnection limit was minimal due to the relative capacity being less than approximately 1%.

A further simplification was required to reduce the nodal points in the larger European model to 58 node points. The Netherlands, Belgium and Germany were represented with one node in the energy mix modelling. This reduction groups all the data within the country together to form one node with associated variables and cross border transfer capacities to other countries. The models were run for each simulation as a separate system and merged with final results in latter stages of analysis. Furthermore, the model sought to solve within a minimum limit of 0.1% of the constraint's solutions at a numerical precision of C_g of 0.001 over a maximum run time of 180 seconds. The regions with the least cost, yet highest and least variable capacity the time periods assessed in this work were elected as the most suitable sites for generation. Figure 79 illustrates the simplified process to derive results for each node.

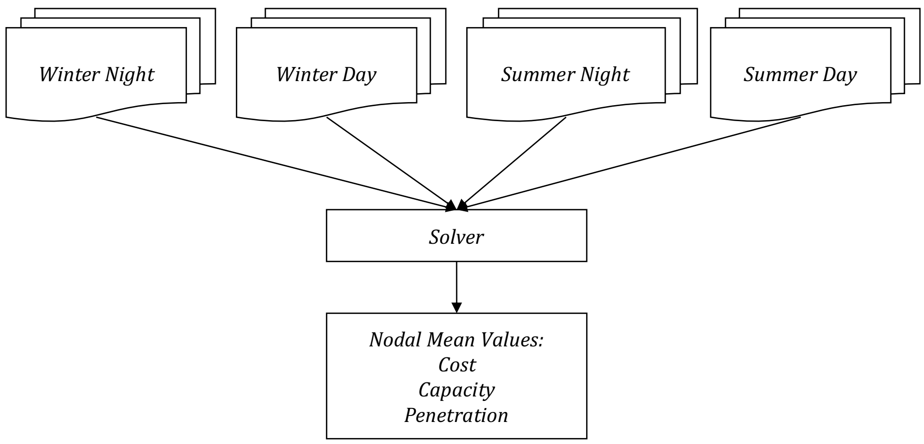


Figure 79. Individual temporal simulation combined output.

Regions which have limited connection capability as set out in section 7.5.6 but have suitable low-cost stable generation potential could therefore indicate viability for transfer capacity improvements. A secondary use of the model was to set the regional transfer capability to capacity requirements of the floating WWE allocation capacity. By doing so the model demonstrates in an 'ideal' scenario the location and magnitude of improvements. It was known that line power flow has an impact on the energy mix and the subsequent ability to absorb variable power generation. Although not pursued in this work the work could be expanded to include line flow constraints across Europe in a power flow model and has been discussed in further work 10.1.6.

7.8.4 Parameter sensitivity

In order to test whether the fit of the solution identified could be considered optimal three parameters were tested, population size, mutation rate and convergence. These iterations were configured to two base scenarios of 58 and 21 nodes representing the larger European and Iberian system. The base case used a set of approximated mean variables for each node. It was known that due to the variable count not changing between simulations of the two models the same optimisation parameters could be used. Population size was significant because it determined the number of subsets for each individual that could be generated. Mutation rate increased or decreased the diversity in population and therefore influenced the probability of a 'better 'solution that could be found. The mutation and population parameters tested for sensitivity were presented in Table 19. Where the variable count was all nodal generation groups, 174 and 69, for the EU and Iberia models. Individual count was derived as 2 times the variable count giving 348 and 138 individuals for the models respectively. The mutation rate was estimated as number of individuals over a step change value, this relationship was assumed from the work [169]. The population size was approximated from the step change times the number of variables, a similar approach was observed in [170].

Table 19. Solver parameters testing for population size for the base cases of 58 and 23 nodes for the larger EU and Iberian island models.

Population Size			Mutation Rate		
Step	IBERIA	EU rest	Step	IBERIA	EU rest
1	1	69	174	1	0.0072
2	2	138	348	20	0.1449
3	3	207	522	30	0.2174
4	10	690	1740	100	0.7246

The values were simulated from the 1st step against one another, meaning population size step 1 was used for the increasing mutation rates and vice versa. The best outcome of the test cases was therefore assumed to be the most suitable fit of population size and mutation to provide the most stable best solution. The outcomes of parameter sensitivity have been presented in Table 20 and Table 21.

Table 20. Solver parameter solution results for the IBERIA model

Population	Mutation Rate	Time (s)	Iteration	Gen	Final Value (C_g)
69	0.0072	29.950	0	1023	59.681
69	0.1449	32.714	0	4226	61.240
69	0.2174	28.205	0	5295	58.809
69	0.7246	17.768	0	2430	58.241
69	0.0072	29.950	0	1023	59.681
138	0.0072	34.024	0	5194	59.638
207	0.0072	33.821	0	5387	59.812
690	0.0072	33.790	0	4020	60.293

Table 21. Solver parameter solution results for the larger rest of study area, EU.

Population	Mutations	Time (s)	Iteration	Gen	Final Value (C_g)
174	0.0029	26.021	0	7003	58.579
174	0.0575	119.949	0	19868	58.325
174	0.0862	6.880	0	1637	58.772
174	0.2874	20.296	0	4737	58.394
174	0.0029	26.021	0	7003	58.579
348	0.0029	159.714	0	34889	58.313
522	0.0029	96.097	0	37968	58.311
1740	0.0029	436.584	0	132618	58.302

The identified best combined solution was selected for both model types for population and mutation rate. The second solver method parameter to test was the convergence of results. The convergence value represents when the mean fitness of the population does not vary by a 'significant amount'. The value of significance was related to a deviation in percentage from one solution to another. Once the solver generations had reached this stage the solutions were said to be 'converged'. The solver stopped the model simulations after a certain time period where this convergence did not change, the results of this parameter sensitivity has been presented in Table 22.

Table 22. Time without improvement of over time for both models with their associated combined parameters.

Model	Time (s)	Generations	Solution Time (s)	Final Value (Cg)
EU	5	742	8.28	59.209
	15	1883	18.75	59.202
	30	29571	151.31	58.342
	60	30407	103.09	58.343
IBERIA	10	662	6.911	59.789
	20	3380	35.88	60.057
	30	6641	77.064	57.634
	60	6896	82.852	57.704

As time increases the objective function reached a lower cost value and therefore was deemed more suitable. The suitable time parameter of 30 seconds was chosen in both cases as no significant change was observed beyond that point. These values were subsequently rerun three times to observe similarity with a deviation in final C_g values of, 0.001 and 0.07 for the IBERIA and EU models respectively. This minimal deviation demonstrated the suitability of parameters for the two models.

7.9 Port Analysis

The allocation model selected all of the potential sites that could be serviced by a port. However, this value of port coverage was not indicative of actual 'build out' rates. Build out rates in this work referred to the time it might take for an installation be completed. Build out rates larger than two years were considered as a project benchmark indication of viability, similar rates were observed in the Hywind deployment. Projects that take longer than two years to reach completion indicate that facilities may not adequate to satisfy the allocated potential and therefore may benefit from change. This work considers several key factors that influence the build out rate, those include vessel characteristics and port characteristics.

7.9.1 Vessel Characteristics

Due to the limited understanding of how large-scale floating wind and wave arrays will be developed assumptions in assessment were unavoidable. The process assumes that wind and wave devices being were floated or positioned by towing craft to sea once assembled in port or in sheltered waters. Other operations involved with an array build out include the inter array cabling and mooring laying and were factored into the analysis. These operations were considered in this configuration of installation to be pre-assembled at site prior to installation of devices. Therefore, the duration was considered to be separate to turbine load out. Installation times for floating wind moorings were observed in [34] to be 12hrs per suction anchor 0.5hrs per 100m depth the same characteristics were assumed for wave with eight hours assumed for drag anchors. The characteristics of installation vessels considered were therefore assumed and represented in Table 23.

Table 23. Vessel characteristic limits assumed from comparative assessments into the UK offshore fixed wind round 1 and 2 projects [171]. Similar vessel types have been assumed for use as technology and subsea operational installation, moorings. Travel times were assumed from [34] for Hywind and an approximated wave .

		Vessel type		
Characteristic		Transport Wind	Transport Wave	Mooring & Cabling
Speed (km/h)	Low	7	10	18
	Mid	8	12	20
	High	9	14	22
Wave Height (m)	Low	1	1.5	2
	Mid	1.5	2	2.5
	High	2	2.5	3

The installation conditions were assumed a more restrictive wind turbine installation due to the increased size of the technology and complexity of manoeuvring. This assumption was based on the installation restrictions seen in the fixed offshore wind industry for turbine installation and Hywind demonstrations [172]. The climatic conditions maximums for the vessel types were modelled using the same techniques and data established in section 4.3. The met-ocean data from the hindcast modelling were combined with installation vessel characteristics for hours of suitable operation. The total number of hours for conditions less than operational limits to occur were established for each cell in the allocation model.

7.9.2 Port Characteristics

Ports are inherently interlinked to vessels due to the varying degree of accommodation available. This work has already addressed the vessel limitations seen in ports through the assessments seen in sections 7.6.4. However, these limitations can be reformulated in a time-based metric and were used in this analysis to address port build out rates. The number of vessels that can be accommodated was dependent on the space in each port category used in this work. Table 24 demonstrates the simultaneous vessel accommodation per port type.

Table 24. Number of simultaneous device load out operations for each port category and the associated high and low values tested for sensitivity. Where load out n was dependent on the port characteristics observed in appendix 12.6.

	Wave (n)			Wind (n)		
Category	Low	Mid	High	Low	Mid	High
S1	1	2	4	0.5	1	1.5
S2	2	4	8	1	2	3
S3	3	6	9	1.5	3	4.5

The high and low simultaneous rates were chosen to reflect variables considered observation throughout this work. However, the application of a standard metric to ports of varying shapes contains uncertainty. Therefore, wave energy load out was chosen to vary by 100% and wind energy by 50%. This reflects the restrictions imposed by port operational limitations observed in section 7.6.

7.9.3 Assessment Method

Using data from the allocation model, port and vessel characteristics assumes an assessment can be made into the number for days required to build out an array within a given two year period. A similar process was observed in the Hywind installation over 2 years with similar set of time scales for phases of operation [172]. Table 25 outlines the site based variables from allocation modelling and the pre device installation period of operation. This phase in development was assumed to occur prior to the installation of turbines. While Table 26 outlines the duration for devices per trip in a single load out.

Table 25. Scenario examples and data with pre device load out installation times based on travel times from vessel attribute data installation process over depth and distance for the total quantity of devices.

	Site variables from Allocation			Pre-Device Installation	
Scenario	Quantity	Depth (m)	Distance (km)	Mooring (Days)	Cabling (Days)
1	200	100	50	312.7	125.0
2	200	100	100	312.9	250.0
3	200	100	150	313.1	375.0
4	200	100	200	313.3	500.0
5	200	100	250	313.5	625.0

Table 26. Scenario examples of load out travel times for devices for 1 device per operational load out per vessel trip.

Scenario	Travel Days	Site time (Days)	Time Out (Days)
1	0.52	0.50	1.52
2	1.04	0.50	2.04
3	1.56	0.50	2.56
4	2.08	0.50	3.08
5	2.60	0.50	3.60

As distance increased, the time per trip increased. However, build out operations for floating wave and wind devices were assumed to be towed out preassembled to site using tugs and smaller specialist craft. With the fixed offshore wind industry extensive jack up barges and large turbine handling craft are required at large cost. However, the pre prepared site mooring and cabling operations require less onsite heavy operations. Therefore, it was assumed that increased levels of tugs or towing craft would be appropriate for such operations rather than one device build out per trip. A distance weighted function determined how many towing craft would be in operation in a build out phase based on the distance to site, as illustrated in Figure 80.

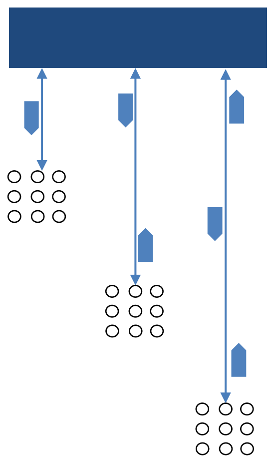


Figure 80. Distance weighted increase in number of vessels in installation load out.

The limitations of such operations were driven therefore by distance to site. However, the maximum number of towing vessels suitable per port per development was restricted by the port capability. The space in port for multiple operations restricts the number of vessels which can operate in sync. Furthermore, the time taken in port to complete assembly of devices and prepare them for load out was known to be problematic. These factors were considered in Table 27 along with the total build time per project scenario.

Table 27. Using the operational time, the distance weighting factor determines how many more vessels could be service in the load out time. Example load out total with and assumed total 730 days in two years.

Scenario	Port Time (Days)	n Vessels	n Per trip	Trips	Install Days	Total Days	Time Ratio
1	0.50	2.0	4.0	50.0	51.0	416.0	0.57
2	0.50	2.0	4.0	50.0	77.1	562.0	0.77
3	0.50	3.0	5.0	40.0	82.5	691.5	0.95
4	0.50	3.0	5.0	40.0	103.3	833.3	1.14
5	0.50	3.0	5.0	40.0	124.2	975.2	1.34

The time ratio dictated a ports viability for successful operations based on the sum of installation phases. In the example scenarios presented, one to three would be considered suitable for operations while four and five would be limited to the time frames for a development.

7.10 Chapter Summary

Infrastructure allocation modelling was conducted in this chapter to establish the roll in which capability has on development cost and potential. Initially the computational problem of connecting individual cells in an allocation model was found to be too limiting. Further, practical assessments confirm that array sites would be formed into clusters of lager arrays ranging from 100 – 900MW in rated size. This simplification provided a suitable level of array potential clusters that were modelled through an allocation process. A bespoke allocation model created in GIS was described and the theoretical capacity of both port and grid infrastructure determined. It was this theoretical capacity that will 'accept' volumes of devices to be grid connected or serviced by port. It was observed that port and grid infrastructure have an effect on the LCOE and distribution of floating technology feasibility in Western Europe. Also observed was that allocation outcomes were highly sensitive to the capacity estimation developed as the theoretical limit. Although it was seen that capacity scales linearly with capacity growth and could therefore be considered suitable for assessment.

A genetic optimisation algorithm process was outlined, and the process involved in evaluating the optimal energy mix in the system with floating WWE penetration assessed. Through considering the demand and transfer capacity, a balance of suitable energy sources was obtained for the lowest possible cost of generation. The temporal variation of such energy sources was considered, and a practical estimate of floating WWE capacity can be made. Port load out analysis was outlined through a spatial analytical method to assess the suitability of ports due to build out rates and associated travels times. The errors associated with both analytical methods have been outlined with the results in the following section.

8. Results & Discussions

Abstract: This section presents the outputs from each contributing models used to derive site suitability. It demonstrates how site LCOE is influenced by port and grid infrastructure capabilities through a number of case studies. It further demonstrates how the tools could highlight infrastructure for growth.

8.1 Introduction

The preceding analytical chapters, three to seven have been a linear process to evaluate the spatial suitability of floating wave and wind arrays and the role infrastructure on suitability. As outlined, each of the models, mooring suitability, energy production, site suitability, LCOE estimation, infrastructure allocation and infrastructure analysis derived key components to answer the research questions set out by this work. They are listed as follows:

1. Where are the optimum sites for industry development taking into account mooring suitability?

2. Where are the optimum deployment areas from a resource perspective?

3. Considering other marine stakeholders where are the optimum sites from a marine spatial planning perspective?

4. Does existing port and grid infrastructure affect the selection of sites for exploitation?

5. How would infrastructure capability changes alter the overall deployment areas and associated costs?

6. Where are the optimum sites for strategic development and where should infrastructure be developed to satisfy the needs of developments?

These questions are referred to in succession with the results in this section. Three groups of work are presented that combine research questions, methods and outputs. They form the basis of the three core site assessments and the final combined assessment, those being:

- Basic site potential (Section 8.2)
- Costed site potential (Section 8.3)
- Infrastructure Assessment (Section 8.4)
- Floating Energy Development Strategy (Section 8.5)

As the thesis has progressed the approaches to resolve these questions have been examined. The combinations of how and where infrastructure should be located has been addressed through the application of case studies as discussed in section 2.5.3. The case studies include:

- Technology cost reduction forecasts from 2018 to, 2020, 2025 and 2030
- Pre-determined infrastructure upgrades from 2018 to 2020, 2025 and 2030
- Energy partnerships for 2018 and 2030

The outcomes are inherently linked to the inputs and assumptions as stated throughout the modelling process. The outputs represent the potential development pathways for floating spar buoy wind and heaving point absorber wave technology. The following sections outlines all of the thesis research questions and the associated results. The results are presented as the identified sites for development, the sensitivities to infrastructure and the suitable areas highlighted for improvement.

8.2 Basic Site Potential

In order to forecast requirements to support growth of floating energy technologies an understanding of where these technologies might operate was required. Therefore, the analysis and results are inherently related to the technology type and the case studies selected. However, the input for the studies could be adapted to allow for further analysis of a wider range of technologies. mooring suitability and power production modules were designed individually to fit within the site selection model as input layer variables, as described

Figure 32.

8.2.1 Mooring Suitability

The first factor driving the site location identification is the characteristic of the technology itself, mooring suitability. This is based around the first research question defined as:

1. *What is the impact on sites for industry development taking into account mooring suitability?*

The spatial mapping process considered the technology specifications and mooring configurations. The study zone was assessed, and extremes removed to provide two boundary polygons in which results were produced and analysis was conducted. The combined impact of the analysis on solving research question one is presented in Table 28.

Table 28. Impact of both technology mooring suitability's on the Marine EEZ in Western Europe. With percentage area remaining after spatial reduction.

	Wind		Wave	
Country	%	km^2	%	km^2
BE	0	0	52	944
DE	0	0	49	12613
DK	5	1377	63	17350
ES	11	21435	12	23383
FR	37	66163	42	75104
IE	38	284240	39	291720
NL	0	0	43	22446
NO	51	122400	54	129600
PT	8	22281	9	25067
UK	46	284713	51	315660

Impacts were observed from the depth limitations imposed, with floating wind being limited in shallow water. This resulted in North Sea countries, the Netherlands (NL), Belgium (BE), Denmark (DK) and Germany (DE) having 0% of their marine zone remaining. Comparatively the wave technology limitations of 30m had a more limited impact on these countries. The maximum depth limit of 1000m resulted in a curtailing of countries exposed to sudden sea shelfs located along the Atlantic ridge, this is most evident for Portugal (PT) and Spain (ES) whose marine zone was reduced to 15% and 12% respectively. The best performers overall in were found to be those areas of, large sea zone, intermediate depth and intermediate mooring complexity. Those countries include, The UK, NO, FR and IE for floating wind. While for wave, PT and ES perform worst with the remaining countries being able to utilise over 30% over the marine zone.

Key Findings: This first analytical process highlighted where the deployment of floating technologies would be considered most practical and where associated infrastructure policy would be most suitable. The summary of findings to resolve the first research question is presented in Table 29.

Table 29. Research Question 1 summary of findings across the entire Western European study area demonstrating both percentage average area remaining across each of the EEZ's and the total square km area remaining.

Technology	Average % Area Remaining	Total km^2
Wave	41	913886
Wind	20	802609

The findings presented demonstrate that for both technology types the majority of the Western European EEZ is lost through mooring suitability limitations. While over 20% more marine space is found with wave technology and might suggest increased suitability over wind technology.

8.2.2 Energy Production

The second process conducted in the site suitability assessment and from which further modelling would be conducted was the energy production model. Power production was estimated for both converter technologies at rated powers of 1MW and 8MW. This work revolves around the answering of the research question:

2. *Where are the optimum deployment areas from a resource perspective?*

The second process conducted in the site suitability assessment and from which further modelling would be conducted was the energy production model. Power production was estimated for both converter technologies at rated powers of 1MW and 8MW. These were grouped into cell ratings of 100MW and 36MW and for wave and wind respectively. The annual energy production (AEP) are preliminary outputs explored in section 4.5.2 but are used throughout the work. In both technology cases the areas of the North Atlantic where found to be most favourable with mean values of on average 2.5 orders of magnitude greater than resource limited areas such as the southern North Sea.

The wave energy production values are found best at the fringes of the western Atlantic coast and are more concentrated than that of wind. With hotspots located off northern Spain, west Ireland and Norway and the North of the UK. The wind power production is found to be broader covering almost all of the north part of the study region. While Spain has a localised production hotspot on its north western coast. Wave capacity factors in the top 90 percentile of the number of sites were found to be approximately 30% while the mean was 15%. Wind capacity factors were shown to be significantly higher with approximated mean values of 53% and 63% in the top 90 percentile. It is important to note that the capacity factor average for onshore wind turbines in the UK known to be at a mean of 25%. This comparison indicates the benefits of locating technologies to higher quality resources.

Key Findings: Considering this section and the research question the detailed overview of findings has been presented. The summary of findings to resolve the second research question is presented in Table 30.

Table 30. Research Question 2 summary of findings representing the mean GWh power output across the remaining study area.

Technology	Mean GWh
Wave	12.5
Wind	17.5

The results presented demonstrate that wind energy has a higher average power production for the marine area considered. Although it was identified in research question one that more wave energy marine zone is suitable for the technology. However, of that space not all the wave technology zone is productive.

8.2.3 Marine Spatial Planning

To identify sites suitable for development from a marine management and basic site potential, a bespoke multi-criteria analysis process was established to address the third research question:

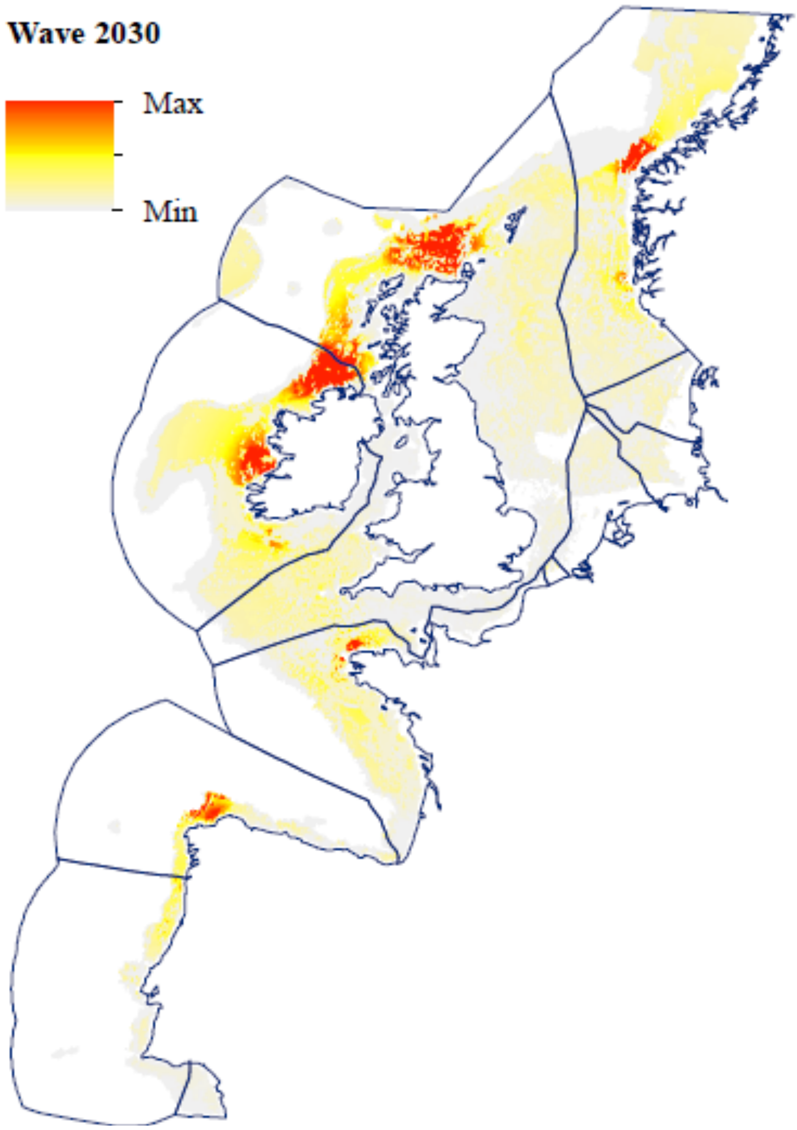
3. *Considering other marine stakeholders where are the optimum sites from a marine spatial planning perspective?*

Marine spatial planning, chapter 5, was used to determine zones of suitable operation with a limited impact to environmental stakeholders and subject to exclusion constraints. These constraints included obstruction risks such as cables, fixed structures, pipes and marine shipping lanes, the results of which are represented in Table 31.

Table 31. Approximated area remaining of individual nationality study zone after exclusion parameters are removed.

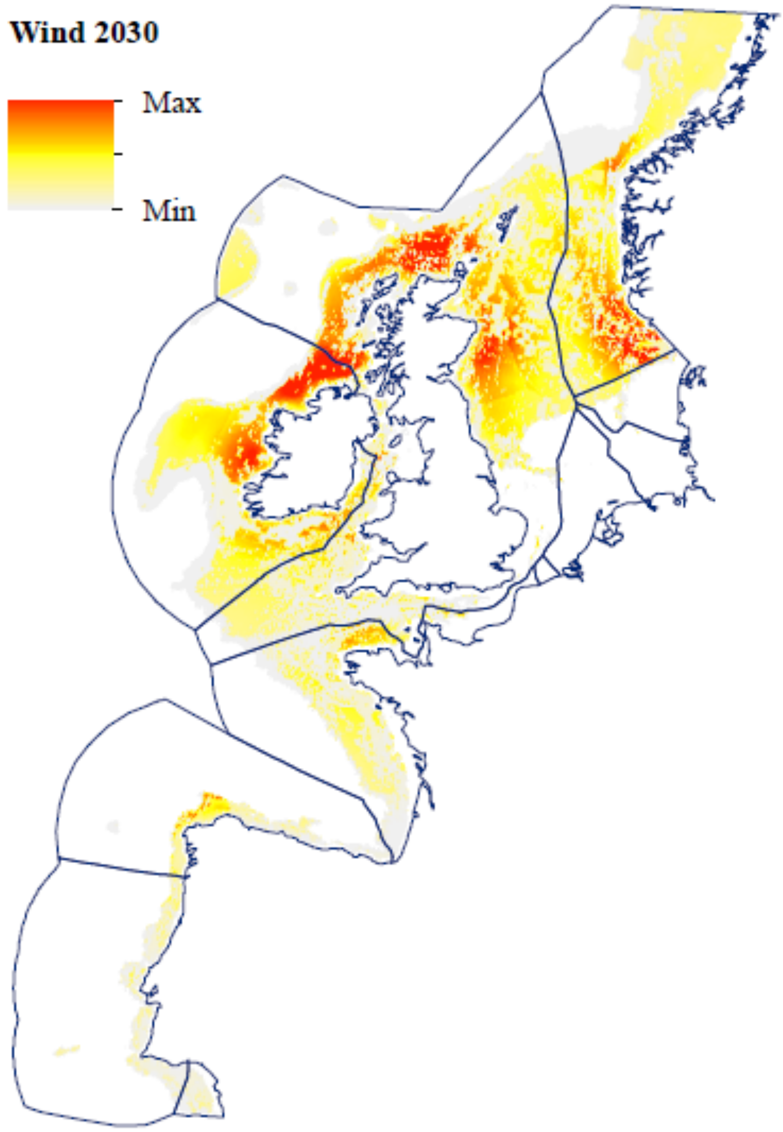
	Wind		Wave	
Country	%	km^2	%	km^2
BE	0	0	62	585
DE	0	0	86	10847
DK	84	1157	84	14574
ES	87	18648	87	20343
FR	95	62855	95	71349
IE	70	198968	70	204204
NL	84	0	84	18855
NO	91	111384	91	117936
PT	85	18939	85	21307
UK	90	256241	90	284094

The largest effect of the exclusions can be seen in countries with limited open ocean EEZ. These include North Sea countries and those with heavily reduced sea zones from the mooring suitability limitations, such as in Portugal and Spain. What is observed is how heavily reduced the Irish Sea zone is with 30% of the remaining area being limited by what was mainly shipping routes. Marine stakeholder restrictions, the level of which is represented in section 5.5**,** included environmental concerns and marine industries of fishing, oil & gas and aggregate extraction. To best evaluate the most viable sites for operation the impact and sensitivity of marine stakeholders was assessed. Those sites least detrimental to other marine stakeholders were scored for site potential. While not entirely limited to floating renewable development, the oil and gas industry is considered a significant stakeholder and therefore, a driver to zonal suitability. Of the remaining study area, the oil and gas industry covers some 25-30% with verifying degrees of limitation. Between 2018 and 2030 approximately 30% of the licensed fields and operational wells in the study zone are to be reassessed or removed entirely and therefore significantly improving floating WWE growth potential. The relative importance of each industry was based on the national value assigned in the method. The result is therefore nationally dependent and sensitive to site assessments across the forecasted time frame. Figure 81 and Figure 82 demonstrates the most attractive site potential for both technologies by a 2030 time frame.



Country	BE	DE	DK	ES	FR	IE	NL	NO	PT	UK
% Area Remaining	0	2	4	3	14	26	4	38	3	66
km2	0	260	525	610	9846	53910	660	44816	533	187502

Figure 81. Floating wave site potential ranging from, 0.4, the minimum accepted level of conflict with other stakeholders to max, 1. minimal impact to marine users and could be the most suitable for technology development. Wave potential concentrations are seen to be more focused on the exposed Atlantic side of the study area owing to the limited resource potential in the North Sea.



Country	BE	DE	DK	ES	FR	IE	NL	NO	PT	UK
% Area Remaining	0	0	6	4	11	22	0	40	6	65
km²	0	0	68	746	6725	43375	0	44554	1080	166557

Figure 82. Floating wind site potential ranging from 0.4, the minimum accepted level of conflict with other stakeholders to max, 1. minimal impact to marine users and could be the most suitable for technology development. Where the combination of site suability and resource has concentrated higher potential around the northern regions of the study area.

Maximum suitability zones located off Ireland, Scotland, Norway, Spain and Portugal show how focussed the industries spatial requirements could be. Areas that do not conflict with other marine users or exceed operational limits for technologies, such as depth are mainly driven by the quality of the resource found. After the marine area was reduced by technical limits, power production limits and exclusion areas the remaining space was assessed for its suitability. Not only to other marine users but also for the technology itself.

Key findings: While suitability was observed for 2018 and other scenarios modelled, the most significant model outcome of this work is the 2030 scenario. This is due to it being the longest term forecast available and the output used throughout latter stages of the modelling process and results. The suitability found inside the remaining area presents a solution to research question three and is represented in Table 32.

Table 32. Research Question 3 summary of findings for the study area for 2030 model outcomes including the cumulative area in square kilometres.

Technology	% Area Remaining	km^2
Wave	15	298661
Wind	16	263105

The findings suggest that a large area of the marine zone is lost to marine spatial suitability, although the values for both technologies are similar. This due to the output demonstrating a more focused scoring for wave technologies and a larger suitability range for floating wind.

8.2.4 Development Cost

The second analytical element in this thesis, costed site potential, considers the role in which LCOE and allocated infrastructure interact. The costs analysis associated with proximity to infrastructure was examined to find an answer for the following research question:

4. *Does existing port and grid infrastructure affect the selection of sites for exploitation?*

The constrained and unconstrained LCOE values discussed in section 6.3 demonstrated the significance of resource and distance to infrastructure or distance to mainland representing an 'ideal' scenario for technology. It is the unconstrained value that remained significant for further analysis as it was used to determine viability for infrastructure allocation. Those sites that have not reached an LCOE with a relative margin of error by 2030 were not included in the allocation analysis. As discussed in this work the relative cost competitive pricing seen in energy markets regularly attributes this value in the range of £100/MWh. Table 33 demonstrates the results relative to this price bracket.

Table 33. Percentage of cells in a LCOE price bracket of below £100/MWh for both technologies across each of the assessed time frames constrained and unconstrained by infrastructure locations.

	Floating Wind		Floating Wave	
	Unconstrained	Constrained	Unconstrained	Constrained
2018	0	0	0	0
2020	19	0	1	0
2025	56	50	10	0
2030	88	83	34	10

What is apparent between the outputs and the percentage representation is the role that location to infrastructure plays on the LCOE of both technologies. With a constrained model, technologies are not competitive until 2025, wind and 2030, wave, while unconstrained they can be cost effective. It was demonstrated that the industry would be extremely limited if constrained by current locations with technology for wave only reaching a sub £100/MWh level at 2030 with 10% of the marine space available. Although the cost of energy limit has been raised to include the LCOE margin of error, the relative influence remains. The results of the unconstrained 2030 LCOE analysis are presented in Figure 83 and Figure 84. Also represented is the location of the first floating wind farm array, Hywind and other potential sites in planning stages.

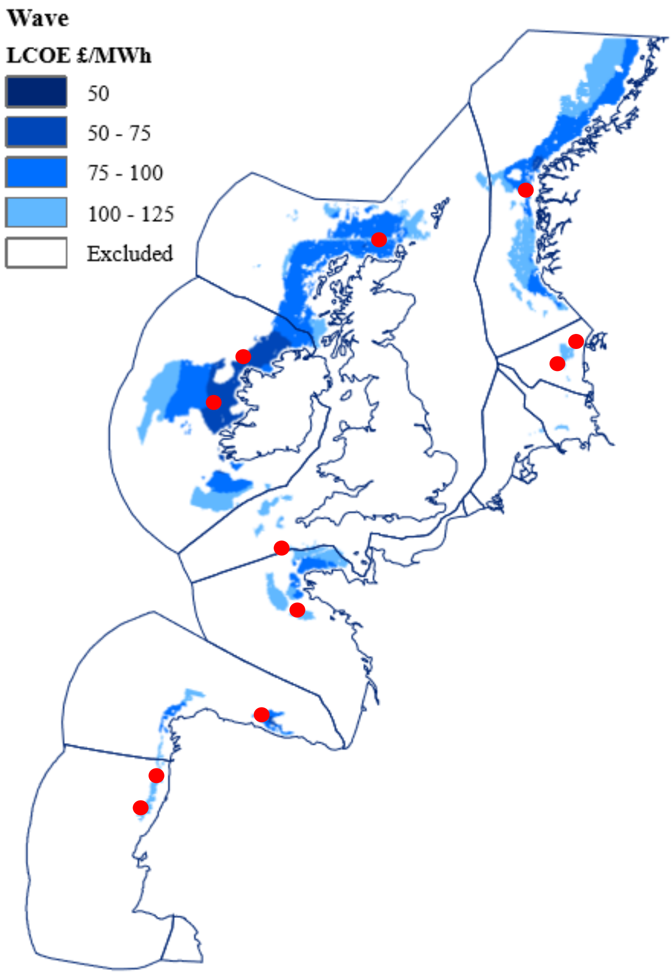


Figure 83. Unconstrained 2030 Floating wave LCOE distributions applied in allocation modelling and (red marker) floating wave energy test sites [23].

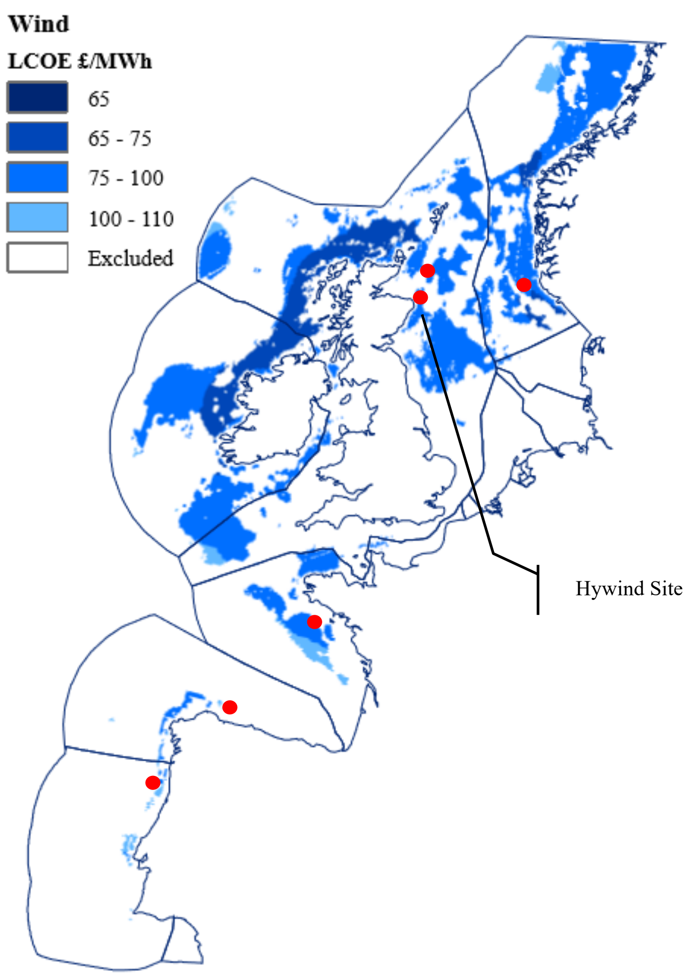


Figure 84. Unconstrained 2030 Floating wind technology LCOE distributions applied in allocation modelling and (red marker) floating wind energy site proposals [98].

The Hywind location is situated in a suitable area for initial development, utilising effective resources and being close to shore, resulting in a low LCOE. However, more attractive but possibly more complicated regions to operate in are observed in the wind distribution. Other prospective floating wind and wave test sites are represented in the outputs that have been deemed suitable in this thesis. This validation demonstrates the suitability of the modelling approach undertaken but also the relevance of the proposed sites for large scale developments.

What is also observed in the results is a further demonstration of the increased levels of wind suitability but more concentrated wave suitability. However, in certain cases large areas of sea zone are lost due to poor resources. In the case of the UK's marine zone the wave energy quality on the east coast is very low and therefore reduces the viability for deployment. For both Spain and Portugal, the remaining sea zone suitable for development is considerably limited. This is not only due to resource however, but also mooring and marine user constraints. A similar wave energy LCOE distribution was observed in [36] and [53]. Within the North Sea, the constraints of floating wind are extremely restricting with Belgium, the Netherlands, Germany and Denmark having few or no sites. However, they do have potential wave energy sites which demonstrates the wider market of the technology compared to the floating wind technology chosen. Although this might change with different types of floating technology, the likelihood is that these countries will pursue a fixed wind design due to seabed conditions in the North Sea. However, the comparatively low LCOE spots of Northern Ireland the United Kingdom and Norway demonstrate the high potential sites for this type of technology.

Key Findings: Research question four was proposed to explore the relationship of cos and existing infrastructure, unconstrained by infrastructure. This section has outlined those findings and the summary of the area remaining at a competitive price by 2030 is presented in Table 34.

Table 34. Research Question 4 summary of findings for percentage area remaining in the study area with an LCOE below £100MWh in 2030 including the potential installed capacity at the rated capacity for a 2km^2 cell and the output recorded at each cell in TWh.

	% Area	km^2	GW	TWh
Wave	36	107518	5376	806
Wind	88	231532	3705	1667

It becomes apparent when drawing a contrast between the two technologies that floating wind has larger opportunities in terms of area for cost effective deployments, but with reduced installable capacity due to its lower capacity concentration at 0.032GW per 2km^2 against 0.1GW per 2km^2. This is in contrast to the preceding results which demonstrated that more space was available for wave energy technologies when not considering costs. However, the wave energy portion remains a significant segment of the remaining sea zone as well as the larger share of installed capacity with over 1671GW available. Although, owing to wind capacity factors being 2-3 times that of wave, the power output is considerably larger which demonstrates the increased area for cost effective deployment opportunities. The EU consumed over 3100TWh in 2017, the results of this thesis, demonstrated in Table 34, show that both floating technologies could contribute a significant portion of that demand. However, as the following results will demonstrate, the effects of realising this potential is subject to infrastructure suitability.

8.3 Costed Site Potential

Theoretical port and grid Infrastructure capability was defined using two characteristics of hosting capacity and weighting for connection. These characteristic variables were used in the allocation modelling to assign the volume being serviced by ports and the volume grid connected. This was assessed through a number of case studies as defined in section 2.5. Understanding the roll that the location of suitable infrastructure has on the growth of floating technology development has been assessed through exploring research question 5:

5. *How would infrastructure capability alter overall deployment areas and associated costs?*

The results of the allocation of potential to infrastructure is represented in this section in two main parts, namely, the spatial distributions of all of the countries and the combination of countries forming infrastructure energy partnerships. Further, the results demonstrated show each forecasted scenario for both technologies. The results presented in this section highlight the LCOE of each simulation as well as the volume of connection to infrastructure locations. Further, the percentage ratio of coverage for current infrastructure capability levels to satisfy array potential are presented for each infrastructure type.

8.3.1 Forecasted Infrastructure Impacts

The known infrastructure developments have been assessed for their impact on cost and the cell coverage in the Western European marine zone. The first simulation combined each individual country's grid capability and modelled them separately to demonstrate the national capability. However, ports were allocated 'globally' (defined as study wide) as it is understood that port infrastructure is not at the same level of national interest and being commercial enterprises conduct multiple operations for multiple project partners. The first case study assessed the distribution of current technology LCOE with zero cost reductions but for current and future, 2020, 2025 and 2030, infrastructure growth.

For floating wind, the total amount of allocated cells grew in deployment over 2.91% (2018), 2.95% (2020), 3.11% (2025) and 3.45% (2030) of the total cell potential. The largest change is from 2018 to 2030. The planned port and grid upgrades factored into the model demonstrate an impact on the volume of arrays that could be installed. Floating wave demonstrates a smaller change in the volume of deployment growth with study area totals of 1.39% (2018), 1.38% (2020), 1.39% (2025) and 1.48% (2030). The increase is only evident in deployment at the latter stages of infrastructure upgrades of 2030, while other total volumes are minimal. This result represents a phenomenon observed where few cells but with larger MW capacity are being connected and at lower cost.

8.3.2 Allocation Outcomes

The largest contrast observed across the results for both technology LCOE's is seen between 2018 and 2030. These two time frames represent the largest variation in technology maturity and infrastructure status, while 2020 and 2025 model output is displayed in 12.8 . The following four plots are presented for both technologies and both time frames representing the roll out for each country's individual grid network and a 'global' overall port allocation model.

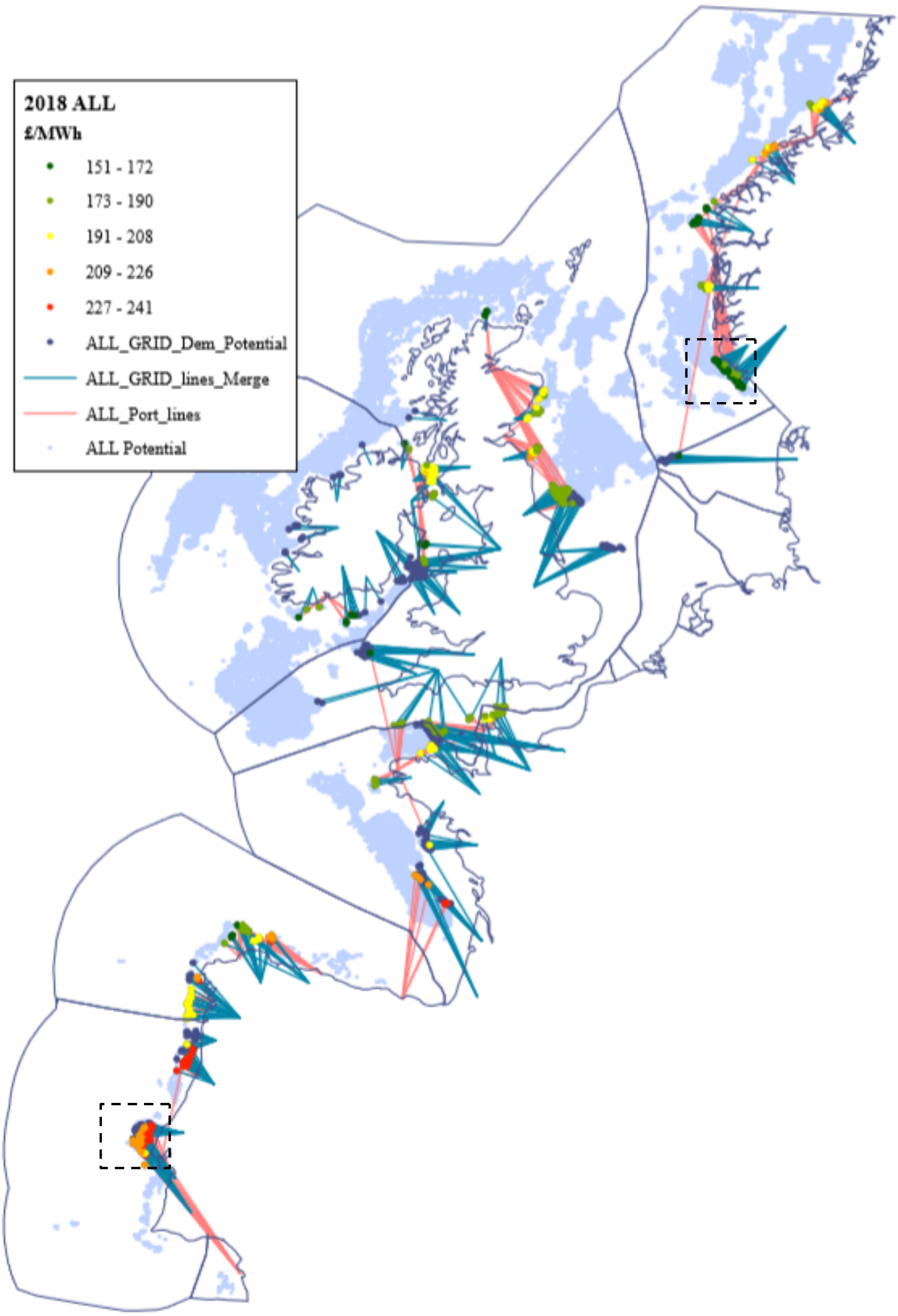


Figure 85. 2018 Wind LCOE distribution with a potential national capacity of, 20GW (UK), 1.5GW (IE), 15GW (NO), DK, 0.1 (GW), 6.6GW (FR), 8.7 (ES), 10 (PT). While the cross border nature of grid and port connections and the roll infrastructure location plays in accessing the lowest cost price cells with highest energy yield. While the highest capacity regions with the lowest cost where found in the North Sea and the poorest of the coast of Portugal.

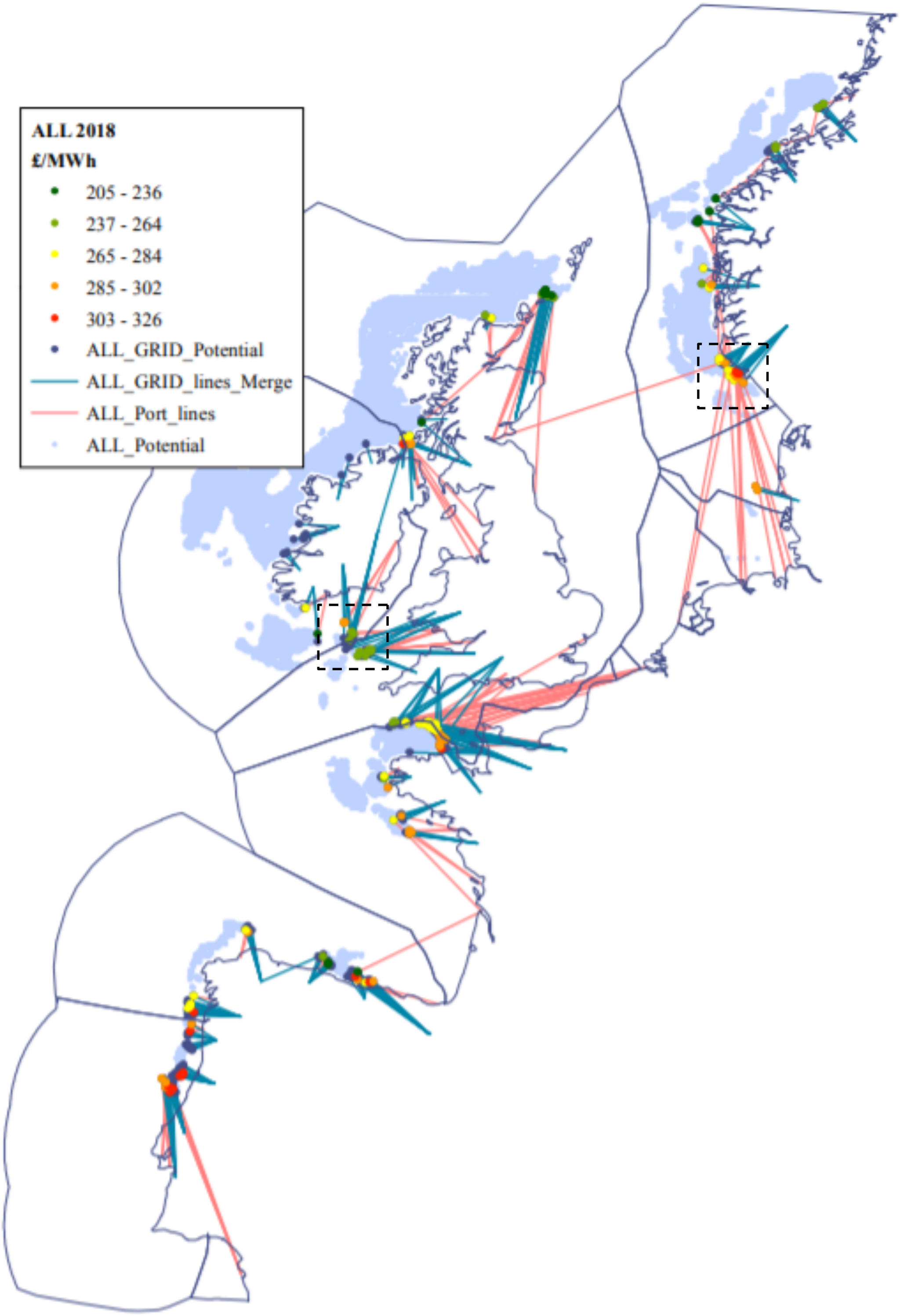


Figure 86. 2018 Wave LCOE distribution with a potential national capacity of, 9.5GW (UK), 1.5GW (IE), 9GW (NO), DK, 0.5 (GW), 6.9GW (FR), 3.3 (ES), 3.8 (PT). While the cross-border nature of grid and port connections and the roll infrastructure location plays in accessing the lowest cost price cells with highest energy yield. While the highest capacity regions with the lowest cost where found in the Irish Sea and the poorest of the coast of southern coast of Norway, a result attributed to poor wave power.

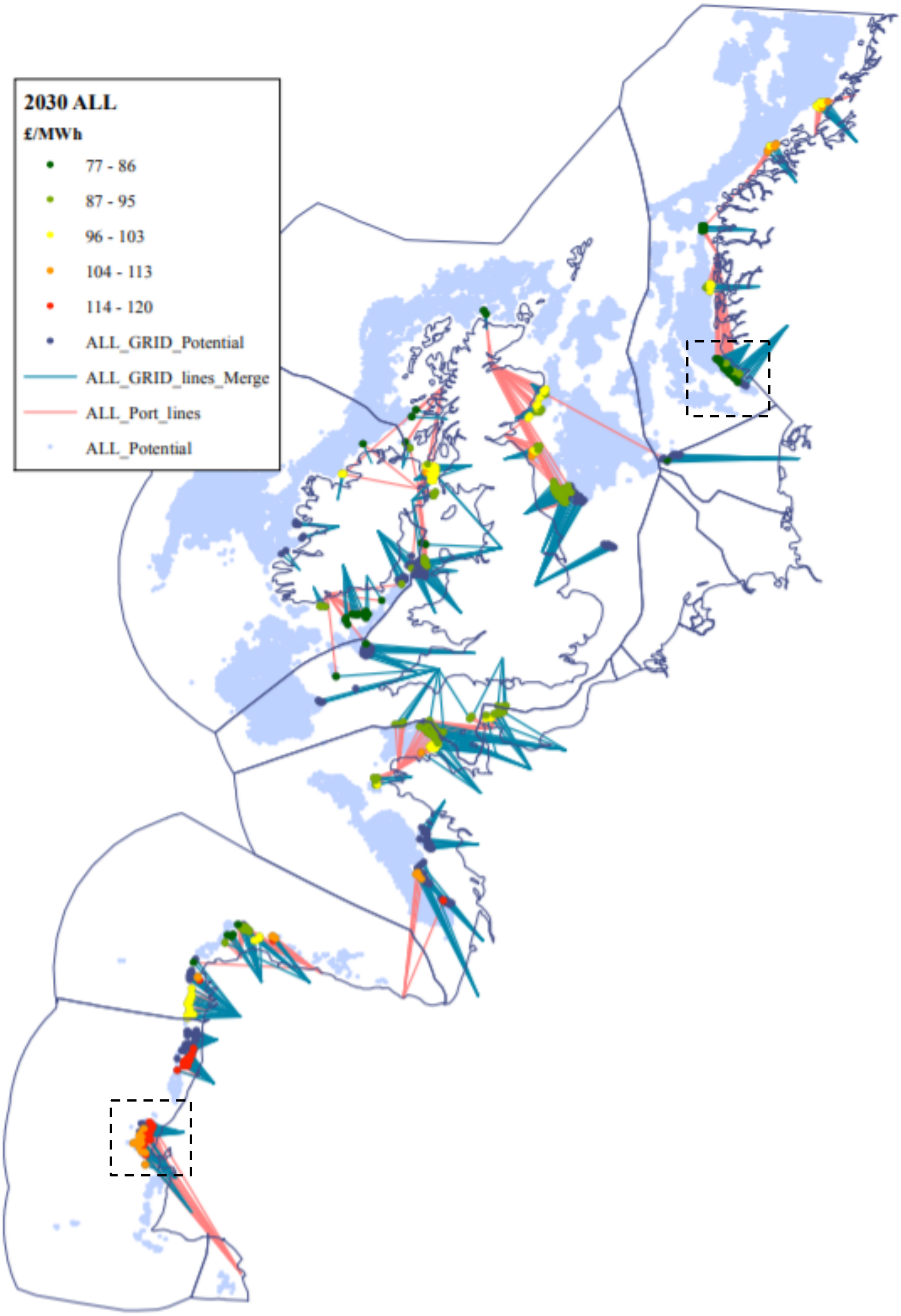


Figure 87. 2030 Wind LCOE distribution with percentage ratio of coverage. With a potential national capacity connection of, 20.5GW (UK), 4.1GW (IE), 15.4GW (NO), DK, 0.2 (GW), 10GW (FR), 8.8GW (ES), 11GW (PT). While the cross-border nature of grid and port connections and the roll infrastructure location plays in accessing the lowest cost price cells with highest energy yield. In the 2030 scenario, the majority of sites are noted as being below £100/MWh while Norway has kept the highest capacity yield cluster. Portugal, however, has improved but remains the wort performance.

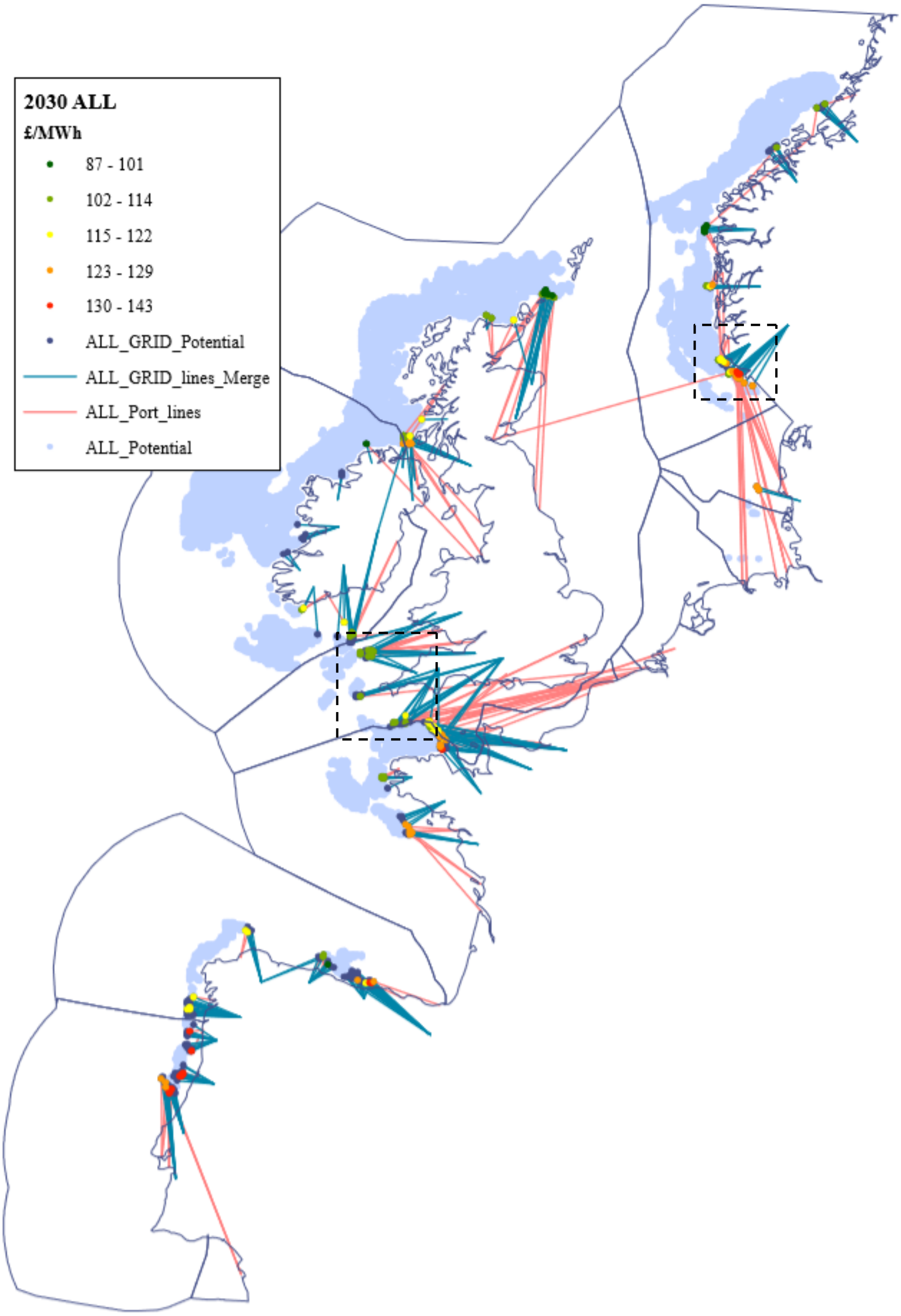


Figure 88. 2030 Wave LCOE distribution with percentage ratio of coverage. With a potential national capacity of, 10GW (UK), 1.8GW (IE), 9.6GW (NO), DK, 0.6 (GW), 8GW (FR), 3.2GW (ES), 3.8GW (PT). While the cross-border nature of grid and port connections and the roll infrastructure location plays in accessing the lowest cost price cells with highest energy yield. The best performance cluster for wave capacity is found in the southern Irish sea with sites connected to the UK, France and Ireland all found to be cost effective. While sites of Norway remain the worst performing capacity cluster.

Throughout these results there is the lack of array distribution in the marine zones of the Netherlands, Belgium and Germany, which carry no suitable sites for array development on this scale due to reasons discussed in the preceding results section. The results of the 2018 models are presented in Table 35.

Table 35. 2018 Infrastructure allocation outcomes for both technologies and all study countries. While mean cost of cells is represented with capacity.

	Wind		Wave	
ID	Capacity, GW	LCOE, £/MWh	Capacity, GW	LCOE, £/MWh
UK	20	187	10	258
IE	2	172	2	268
NO	15	178	9	270
DK	1	168	1	291
FR	7	196	7	284
ES	9	195	3	276
PT	10	228	4	310

It is observed that no countries could be considered cost effective for both technologies due to their access to suitable infrastructure. However, what can be seen in the table is the variation in LCOE and capacity. While the UK for example had the highest connected capacity, but poor LCOE, Denmark had very low capacity, but yielded the best LCOE. The coverage of infrastructure for each country is represented in Table 36.

Table 36. 2018 Infrastructure coverage percentage. A ratio of infrastructure coverage has been evaluated for both grid connection volume and port servicing volume. Where the grid coverage is derived as, array potential/array connected volume and port coverage array connected/array serviced volume.

	Wind		Wave	
Country	% Grid	% Port	% Grid	% Port
UK	5	57	2	58
IE	1	22	1	28
NO	3	100	2	68
DK	100	9	100	100
DE	Na	Na	Na	Na
BE	Na	Na	Na	Na
NL	Na	Na	Na	Na
FR	8	33	6	52
ES	21	89	21	27
PT	30	59	41	34
MEAN	**24**	**53**	**25**	**52**

Two extremes can be observed in the cases of Denmark and Norway. While Denmark can grid connect all its wind and wave capacity, it cannot service wind with local ports and can service wave. While Norway does not have enough capacity to cover a marine area as large as its own and therefore has a low coverage, but can however, service the technology deployed. Spain and Portugal use the most of the potential available in both cases and score well in both cases. The wave energy installed potential capacity is on the whole lower compared to wind. This is in large part due to the lack of infrastructure coverage in regions where resource is greatest as seen in the previous figures. It can be determined that, due to depth limitations for the technology and ports, the North Sea is unsuitable. Although this is a known factor for the industry as outlined in this work. The lack of ability to cover grid potentially connected arrays is apparent in Ireland, France, the UK and Norway performing worst due to the higher potential found. The results of the 2030 models are presented in Table 37.

Table 37. 2030 Infrastructure Allocation Outcomes, with capacity and potential in GW, LCOE in £/MWh and Utilisation being the% capacity use of potential.

	Wind		Wave	
ID	Capacity, GW	LCOE, £/MWh	Capacity, GW	LCOE, £/MWh
UK	21	93	10	111
IE	4	87	2	112
NO	15	90	10	118
DK	0	85	0	124
FR	10	96	8	121
ES	9	97	3	119
PT	11	114	4	133

The drop in LCOE is apparent for both technology types with 85% of wind sites being considered cost effective at less than £110/MWh, including a margin of error. Similar was noticed for wave sites with the top 70% of wave sites at less than £130/MWh, including a margin of error. What can be determined in the results is the relatively poor LCOE distribution and coverage in Portugal and countries around the North Sea. Between the two forecasts increases in potential capacity were noticed for wind from, 65GW (2018) to 70GW (2030). Comparatively the change in wave potential capacity was limited with 35GW (2018) to 38GW (2030). This would indicate that although small growth in infrastructure is apparent, the floating wind technology will benefit most from developments, this coverage is further demonstrated in Table 38.

Table 38. 2030 Infrastructure coverage percentage. A ratio of infrastructure coverage has been evaluated for both grid connection volume and port servicing volume. Where the grid coverage is derived as, array potential/array connected volume and port coverage array connected/array serviced volume.

	Wind		Wave	
	2030		2030	
Country	% Grid	% Port	% Grid	% Port
UK	5	58	3	58
IE	1	50	1	30
NO	2	92	2	65
DK	100	9	100	100
DE	Na	Na	Na	Na
BE	Na	Na	Na	Na
NL	Na	Na	Na	Na
FR	9	43	5	51
ES	23	82	20	22
PT	30	62	39	30
MEAN	**27**	**56**	**24**	**51**

Comparing these results highlights the influence of infrastructure gains for wind against wave. The two coverage tables for 2018 and 2030 demonstrate how there is some small growth in some countries, e.g. grid coverage for Ireland. Norway, France, Spain and Portugal also show a little development in terms of coverage between forecasts. Overall the coverage percentage shows an increase level for wind than wave, this is attributed to the port developments occurring that are already focused on wind. This would indicate that facilities could be targeted better to allow for smoother development across Europe.

8.3.3 Energy partnership Scenarios

As defined in the research motivations, a core outcome of this work was to identify how combinations of partnered infrastructure could benefit the industry. The principle, outlined in detail in section 2.5.3, would be to assess how countries that already share close energy system ties could combine grid connection capabilities to support developments. The goal would be to reduce cost and increase support for larger levels of connection without developing new infrastructure. Countries with great potential but limited infrastructure capability could benefit from countries with the opposite. Figure 89 outlines an example outcome from the combination of two countries which could increase the number of cells available at a wider range of costs.

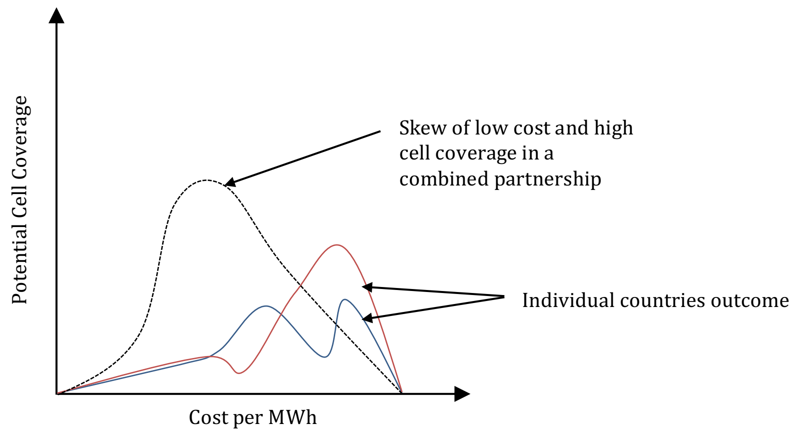


Figure 89. Demonstrative spatial statistical curve showing the benefit, positive skew, of energy partnerships.

Through combining datasets, the model simulates locations based on shared grid links with a 'global' port support allocation. The collaborative energy partnerships identified are discussed in section 2.5.3 and defined as:

- IBERIA – Spain and Portugal
- ISLES– the United Kingdom and Ireland
- CELTIC – the United Kingdom, France and Ireland
- NORD – Norway and Denmark
- NOUK – Norway and the United Kingdom

Partnerships between these countries that have been deemed viable are selected in this work for further analysis. The following LCOE distribution curves for each partnership for forecasts in 2018 and 2030 are represented in Figure 90 for wave and Figure 91 for wind.

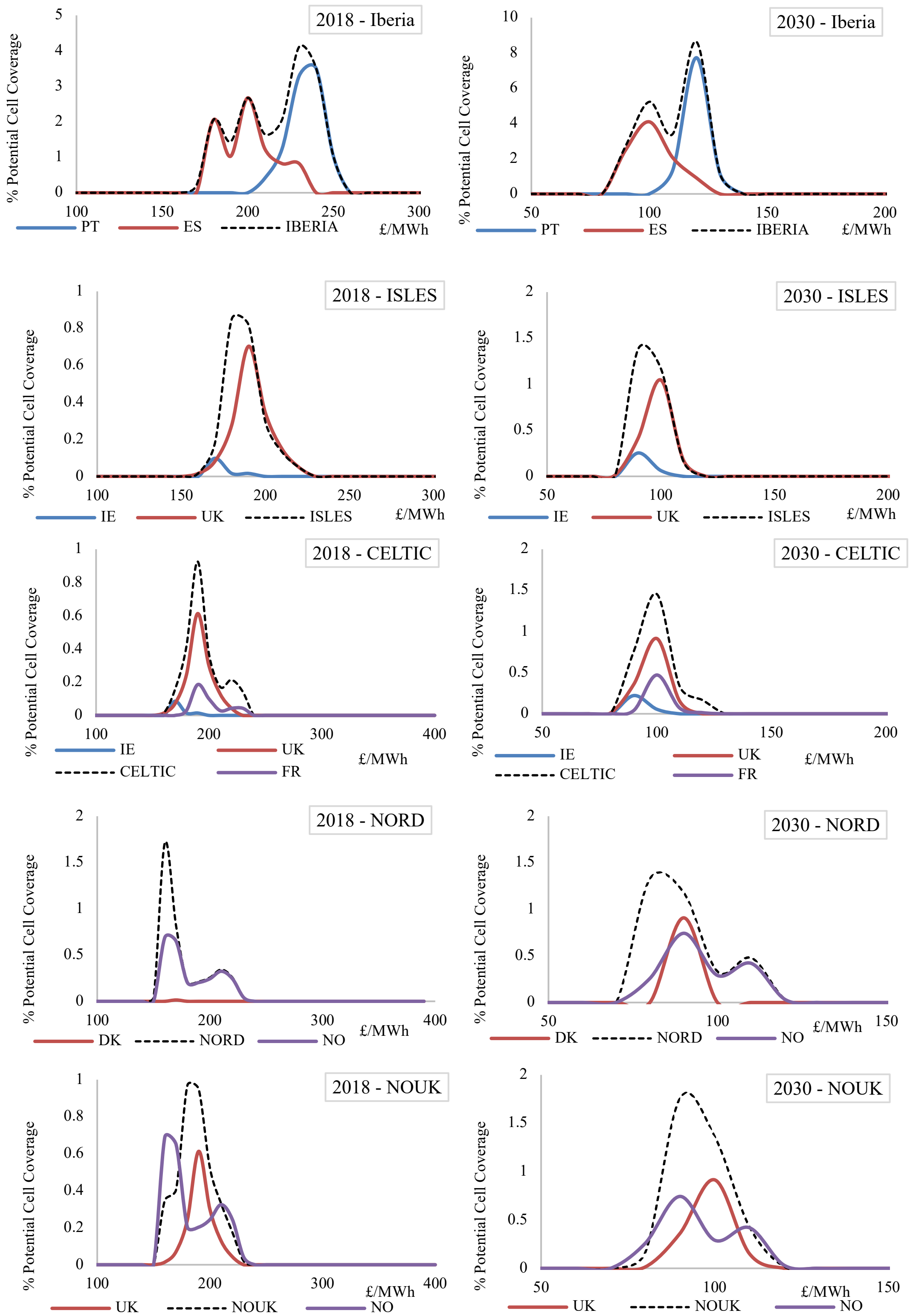


Figure 90. 2018 and 2030 Energy partnership LCOE distributions for wave energy arrays. LCOE can increase when the combined relationship represents a region where there are too few low-cost sites to be allocated to the size of the demand, this is observed in the NORD and IBERIA case studies for example. Partnerships with both a high volume of demand and low cost sites can be seen in the NOUK and ISLES combinations with both examples demonstrating high cell coverage and low costs.

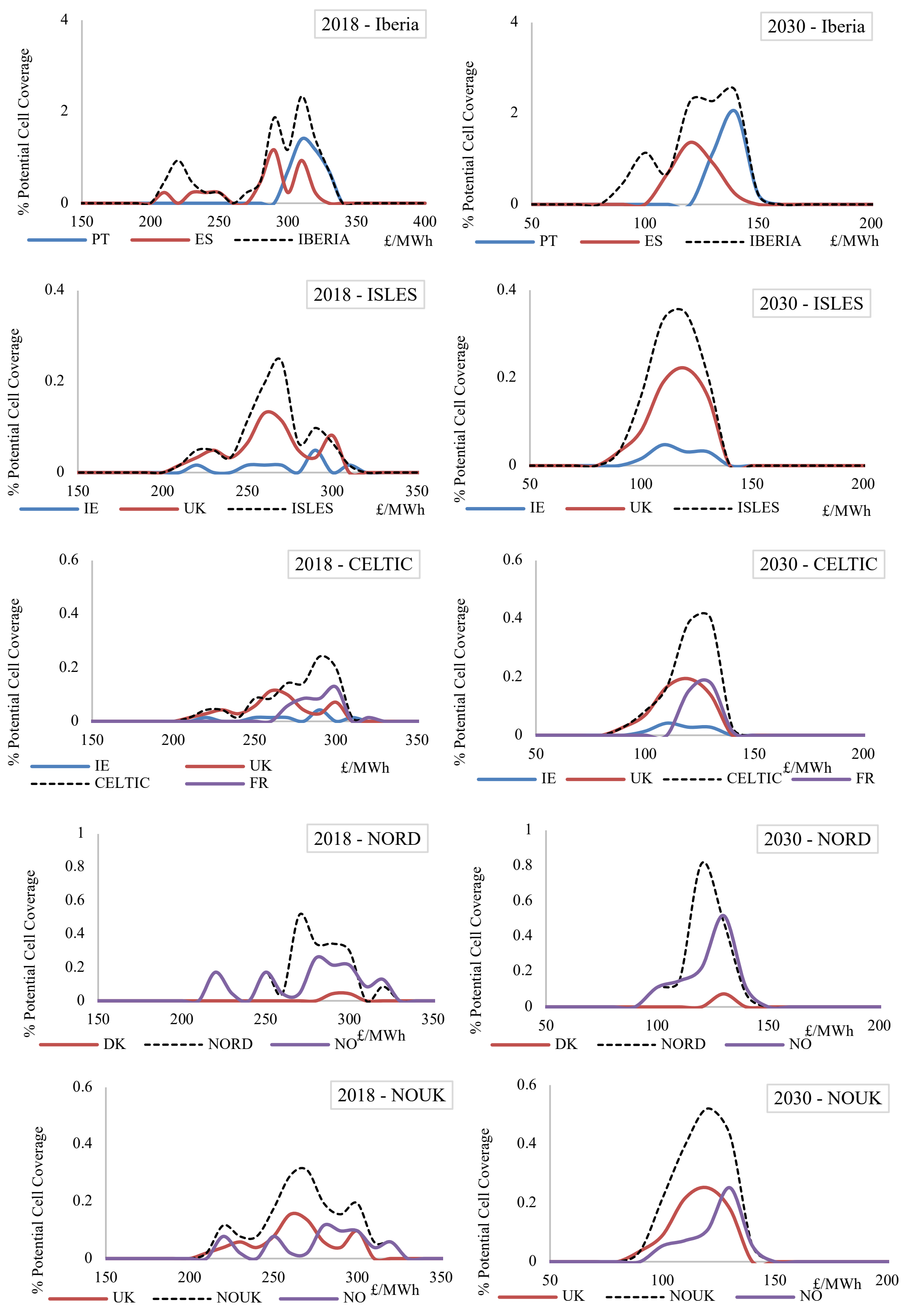
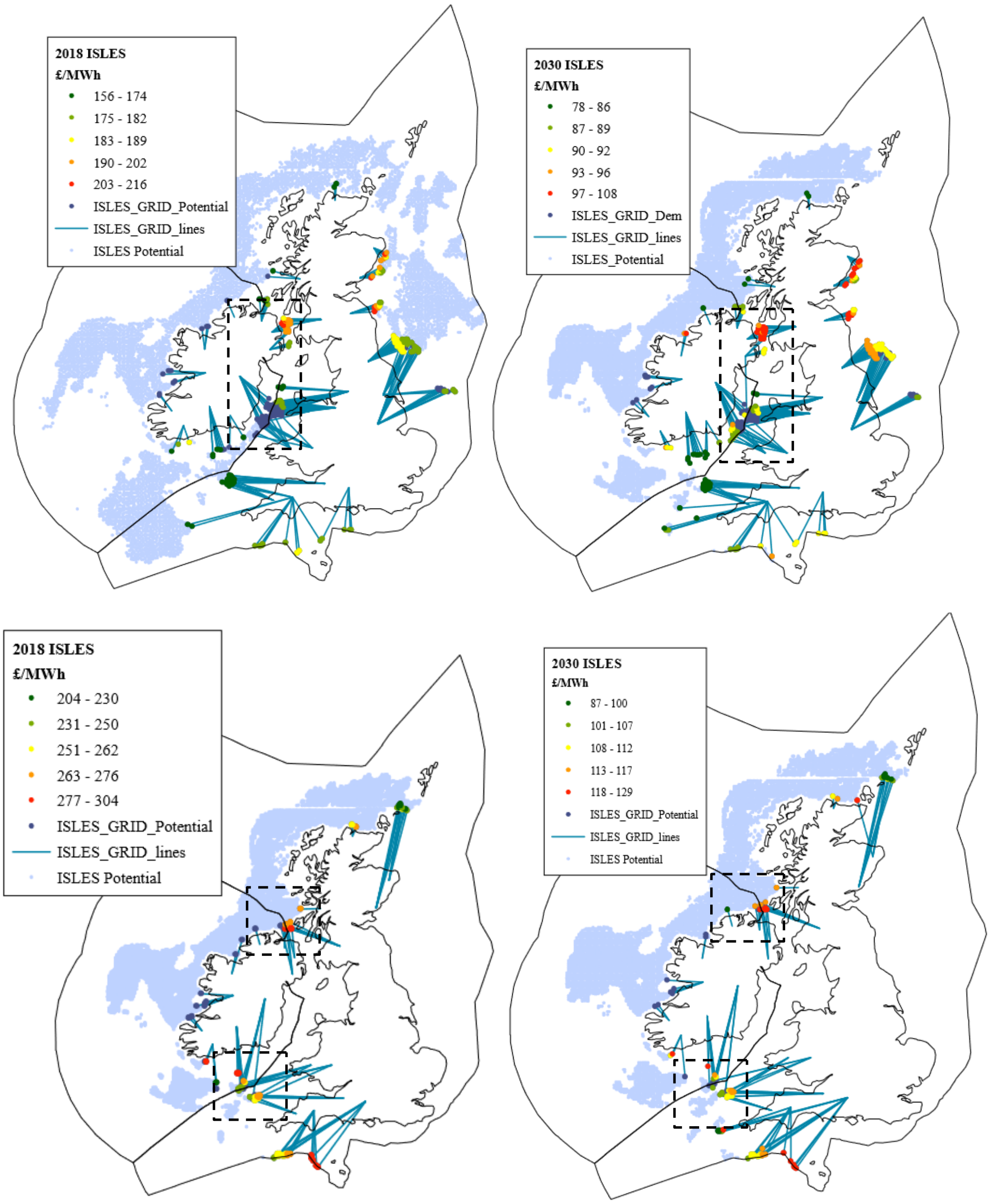


Figure 91. 2018 and 2030 Energy partnership LCOE distributions for wind energy arrays. LCOE can increase when the combined relationship represents a region where there are too few low-cost sites to be allocated to satisfy the demand. This observation is seen acutely in the wind outputs with all partnerships demonstrating a wide spread of LCOE values over 2018. This is due to the limited number of available sites compared to wave. As costs have reduced over time 2030 case studies, the partnerships demonstrate a more concentrated output with higher coverage at a lower LCOE.

The partnership curves demonstrate a change in combined grid infrastructure capability allocation in all cases. What can be seen is the associated increase in potential cell coverage and decrease in LCOE for both technologies in most of the 2030 case studies as lower cost sites are made available. However, it was observed that over the wind 2018 outputs there was a significant increase in spread of LCOE values, in contrast to the more focused LCOE and greater coverage of wave outputs. This is due to the fact that there were a lower number of suitable cells able to satisfy demand and therefore poorer quality sites were utilised by the model. This effect is acutely overserved for the wind model over 2018 owing to the more concentrated cell distribution and lower amount of cells overall. In both models the Iberian case study demonstrates this effect with an extremely limited number of cells available. What can also be seen is the benefit to countries which originally had a small cell coverage and can utilise increased cell area to connect to their grid, which is true for Ireland and Denmark for example in the ISLES and NORD cases. In these two cases the output from the combined allocation demonstrates a positive skew towards lower LCOE and greater coverage indicating a suitable partnership for growth. This is due to the UK's larger demand and grid capability accessing the high potential in Irelands marine zone. This is also true for Denmark which in all cases is extremely limited with its array potential.

The benefit of the NORD partnership proved most impactful for the wind energy cases. Iberian partnerships also showed a positive benefit to collaboration, with far lower wave energy LCOE being accessed in greater numbers. The NOUK and CELTIC partnerships showed some benefit to collaborative allocation, however the curves did not represent enough of a positive skew towards increased coverage or new LCOE coverage. In these cases, the resultant curve demonstrated that comparatively to NORD, ISLES and IBERIA the benefit is low. Therefore, these three have been chosen for further analysis and spatial representation.

ISLES Infrastructure Partnership

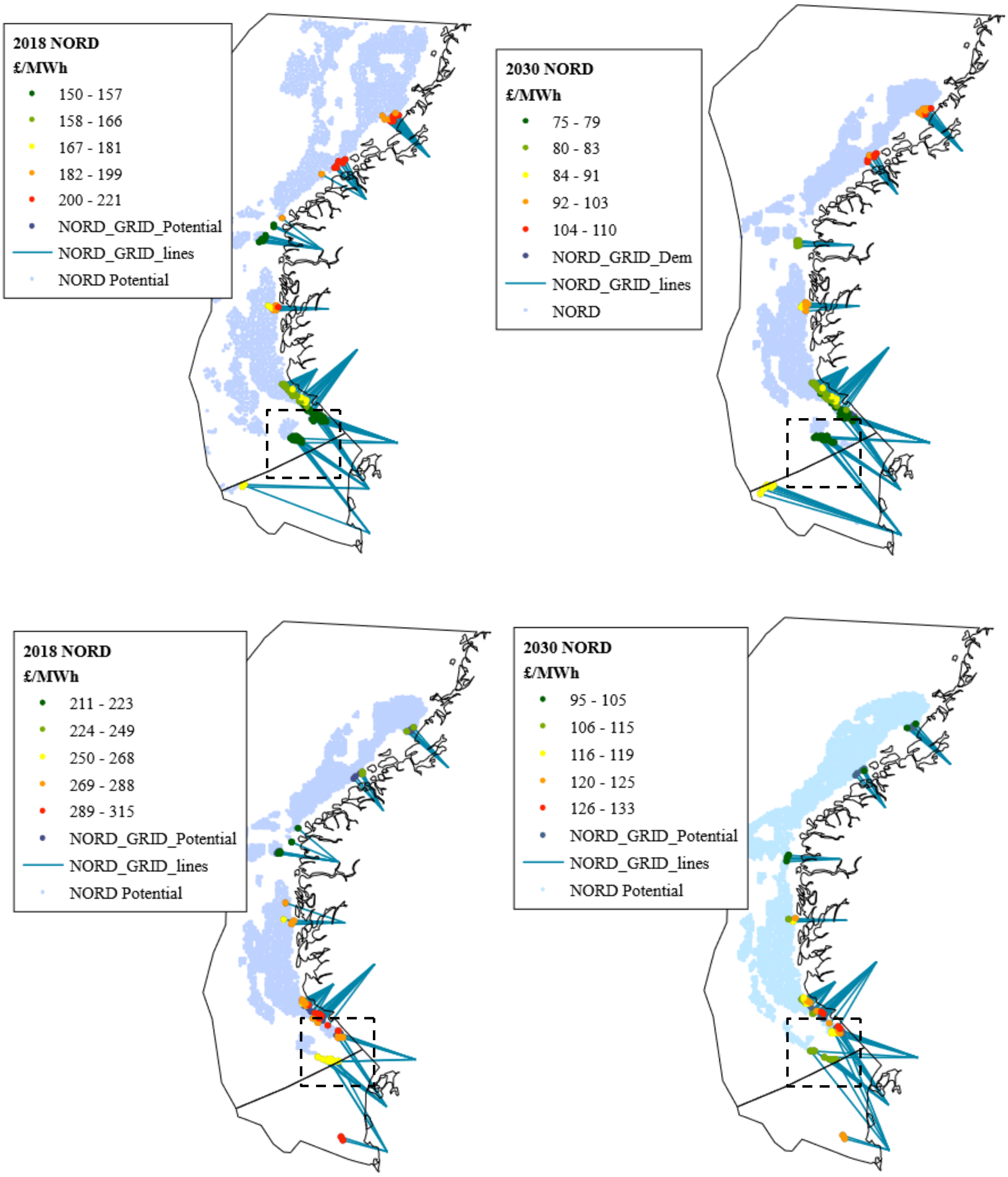


		Wind			Wave		
Type	Partnership	Mean £/MWh	% Grid	% Port	Mean £MWh	% Grid	% Port
2018	ISLES	182.3	3.6	64.1	260	1.5	63.7
2030	ISLES	90.7	3.8	71.4	110.1	1.6	66

Figure 92. Wind (top) and wave (bottom) LCOE distribution with a potential capacity of 31GW and 17GW for wind and wave respectively in 2018 and 38GW and 18.5GW in 2030. Table of port and grid coverage for the associated developments. With dashed boxes demonstrating the most significant deployment of lowest cost connected and serviced sites.

The UK's larger demand and grid capability can access the high array potential in Ireland and is focused along that marine boundary. The dashed boxes in the Irish Sea highlight where that cross border connection is occurring. An increase in installed capacity potential is observed here with the combined partnership achieving nearly 40% increase in capacity of wind and approximately 50% for wave energy. What is also seen is the consistent lack of port coverage on the Irish West coast. Furthermore, a similar lack of grid capability and resultant low allocation is the lack of connection in the north of Scotland.

NORD Infrastructure Partnership

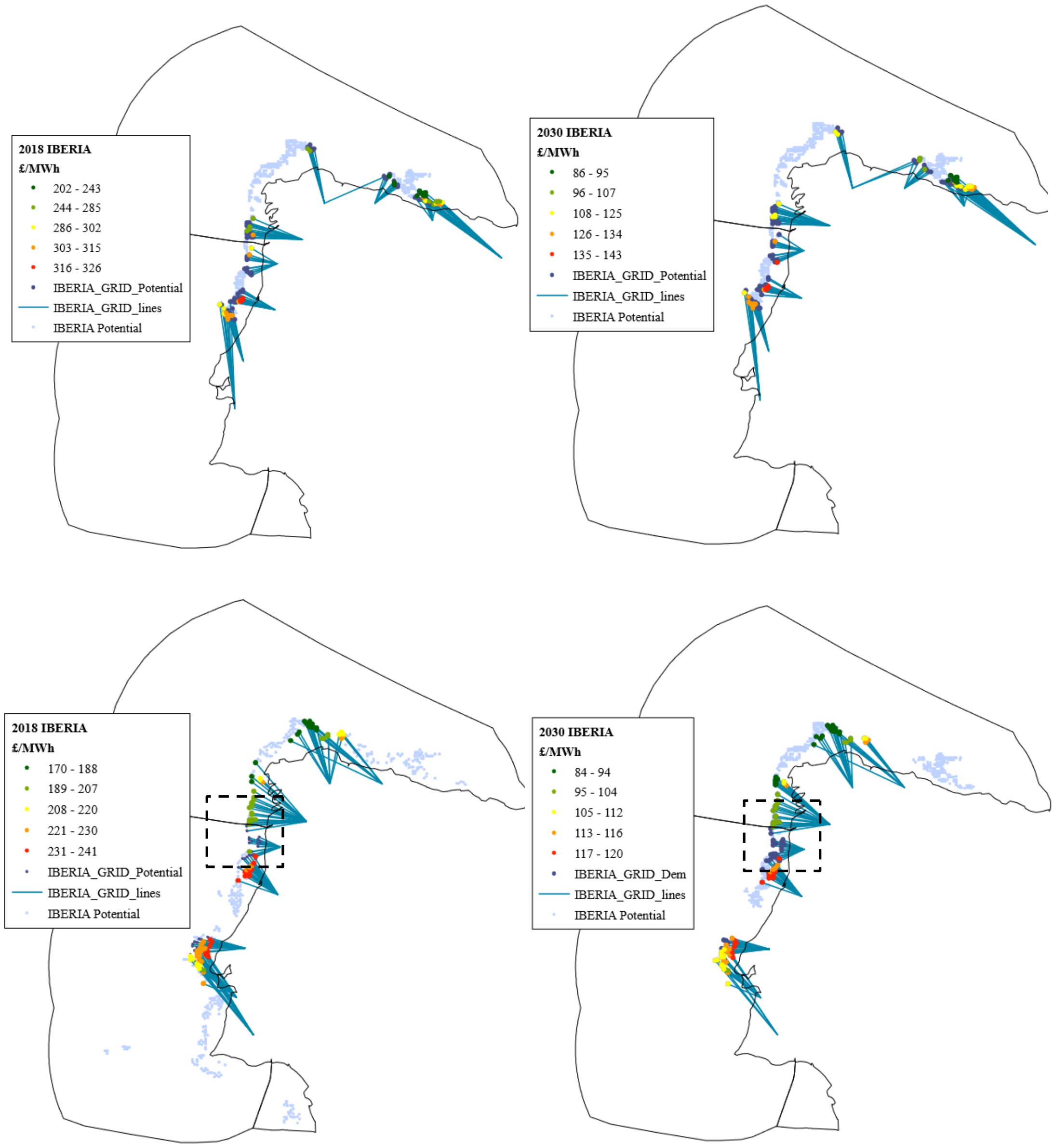


		Wind			Wave		
Type	Partnership	Mean £/MWh	% Grid	% Port	Mean £MWh	% Grid	% Port
2018	NORD	170.9	4.0	97.8	268.7	3.0	68.1
2030	NORD	85.3	3.6	93.8	116.1	2.5	63.8

Figure 93. Wind (top) and wave (bottom) LCOE distribution with a potential capacity of 23GW and 14GW for wind and wave respectively in 2018 and 25GW and 14GW in 2030. Table of port and grid coverage for the associated developments. With dashed boxes demonstrating the most significant deployment of lowest cost connected and serviced sites.

In the NORD case the regional benefit is shown with Norwegian array potential being allocated to the Danish grid. This is due to the fact that Denmark which in all cases is extremely limited with its array cell potential but large grid capacity. The sites that are being allocated to Denmark are of high quality, in the top 25%, of LCOE and could prove to be suitable for development. The port coverage for these two cases proved to be almost full for wind and capable of meeting the top 70% of cells with LCOE's less than £130/MWh for wave.

IBERIA Infrastructure Partnership



		Wind			Wave		
Type	Partnership	Mean £/MWh	% Grid	% Port	Mean £MWh	% Grid	% Port
2018	IBERIA	211.2	25.7	72.8	281.0	26.4	39.8
2030	IBERIA	105.1	28.0	75.6	119.3	25.9	36.8

Figure 94. Wind (top) and wave (bottom) LCOE distribution with potential capacity of 20GW and 9.5GW for wind and wave respectively in 2018 and 21GW and 11.5GW in 2030. Table of port and grid coverage for the associated developments. With dashed boxes demonstrating the most significant deployment of lowest cost connected and serviced sites.

The IBERIA example was chosen due to the increase observed in the LCOE distributions but also the comparative lack in space compared to rest of the study area countries. Furthermore, as the Iberian Peninsula is isolated from the rest of the study area in terms of transmission network and geography, the IBERIA partnerships could prove to be highly advantages to the member states. Although cross border connections are observed in wave partnerships in both forecasts the impact is limited for wind. However, the sites that are allocated in cross border connection are seen to be in the top 25% of LCOE distributions. The increase in capacity is observed in these two cases due to the Spanish connection to Portuguese array locations. The port coverage in this region remains poor due to lack of facilities nearby despite utilising all ports within the allocation distance cap.

8.4 Infrastructure Assessment

The following results demonstrate the outputs of the analytical sections of 7.7 and 7.8 for the grid and ports respectively. The output of this analysis is to further expand the understanding of research question 5 and how infrastructure impacts on the development of floating WWE.

- Cost of generation is examined for the impact floating WWE could have.
- The overall penetration considering all of the factors in the energy mix analysis is evaluated for each of the scenarios.
- The role variability has on the energy mix and how this might change depending on location is demonstrated.
- Further the time frames involved in developing arrays in each scenario is discussed.

The current upper limit of competitive price of energy has been defined in this thesis as £100/MWh. When considering the potential LCOE distributions it has been identified that this value could only be reached at a 2025 and 2030 time frame for both technologies. Therefore, strategic development of infrastructure should be targeted to accommodate this fact.

8.4.1 Cost of Generation

The overall energy mixes in the genetic solver market model are determined by cost of generation, C_g, for each energy source including carbon pricing. Therefore, the location of low-cost floating WWE must also interact with other forms of low cost generation. Each of the model scenarios considered were evaluated for the impact floating WWE could have on the cost of energy in Western Europe. The associated errors with the cost modelling, as discussed in the model inputs in section 7.8 are presented in Figure 95.

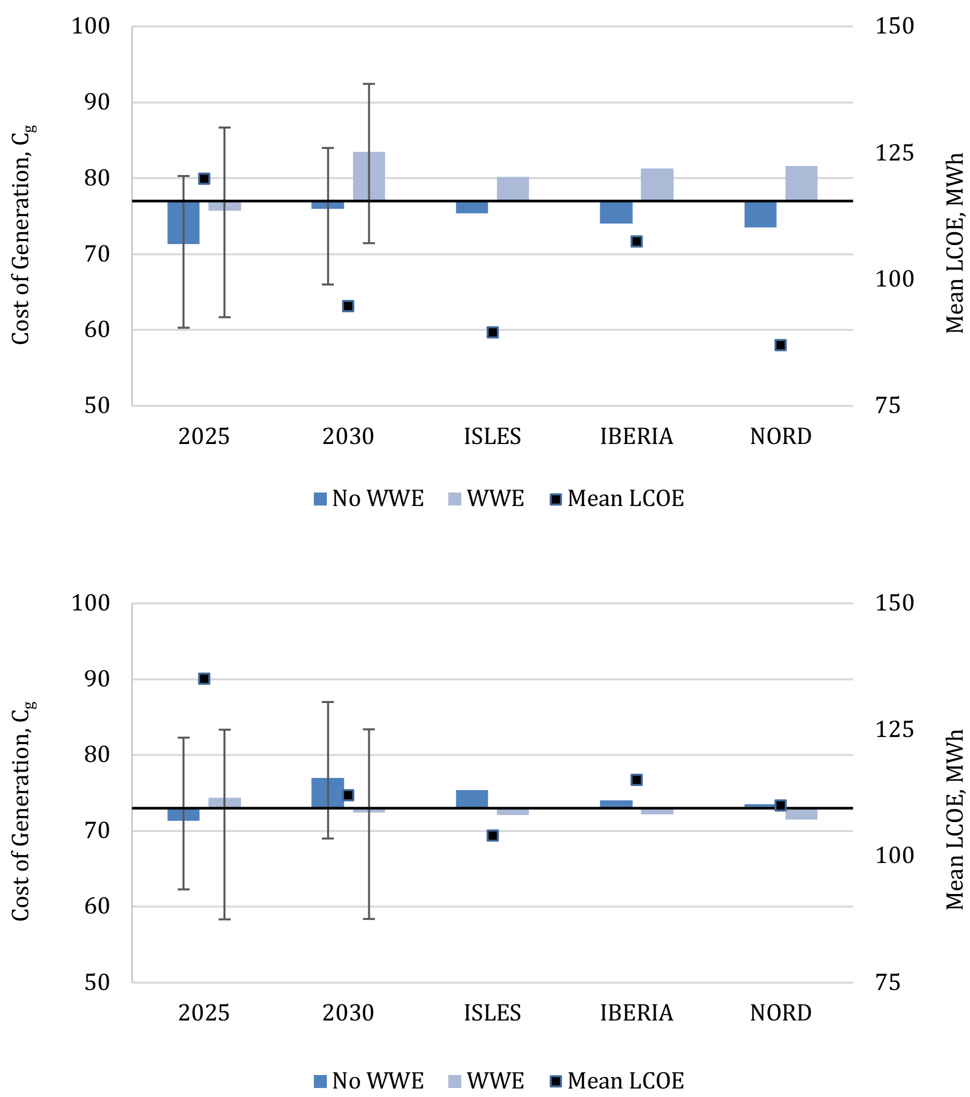


Figure 95. C_g, cost of generation for a 30% renewable mix for wind (top) and wave (bottom) with cost sensitivity to high and low values for 2025 and 2030 models.

What would be expected from the Mean LCOE values for wind and wave would be a corresponding C_g value following the LCOE trend. What is observed in the two plots is in some cases the opposite of this assumption. Wind energy is as discussed in the previous section more likely to be included in the energy mix due to its cost and minimal variability and therefore pushes prices up to mean C_g of 77. Wave energy, however, has high levels of variation and is in many cases too expensive and the overall cost of generation is kept low around a mean C_g of 73. The margin of error seen in these two outputs is relatively large but still represents the same trends. These values are the amalgamation of the cost inputs for energy source and the amount that energy source being utilized. What is observed is that for the models of 2025 and 2030 the errors are more significant for wave energy. Further a mean error of 20% for energy prices reflects a C_g value of 16 and 13 lower than the mean for wave and wind respectively.

8.4.2 Energy penetration

The overall penetration of floating WWE reflects the combined output of the suitability of sites, cost, allocation of infrastructure and grid capability. The output of the market mix models demonstrates how the technologies considered could become part of the national energy mixes. The outputs, represented in Figure 96 and Figure 97 demonstrate the dominance of some countries over others and the influence of Energy partnerships for wave and wind respectively.

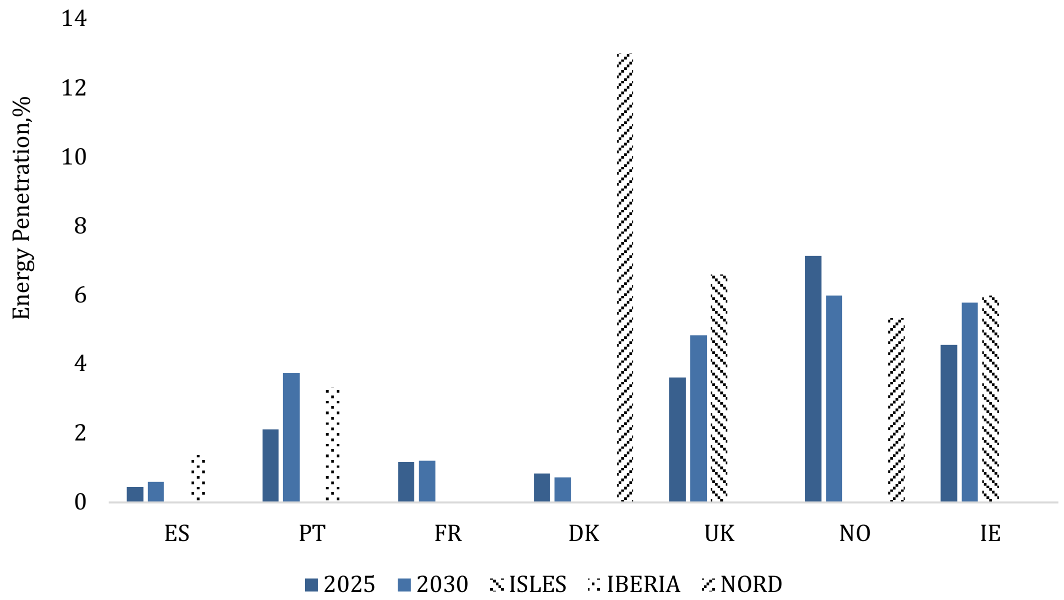


Figure 96. National energy mix penetration of floating wave for the models considered. Where, ISLES = UK + IE, IBERIA = PT + ES, NORD = NO + DK.

What is seen in all, but one case is the trend of growth from 2025 to 2030. The outlier, Norway shows a decline in penetration over time. This is attributed to competition with the already installed low cost renewable energy system. Norway maintains high levels of hydro power with a very low generation cost value. The penetration levels of wave energy are relatively higher for the UK, Norway and Ireland compared to Spain, Portugal and France. This is due to the poor number of suitable sites seen on the coastlines of these three nations. The largest gain in wave energy penetration is seen to be Denmark, which could host a 13% increase over its national energy mix if allowed to utilise Norwegian sites in a Norway-Denmark energy partnership. This outcome is attributed to the higher localised demand and transfer capacity found in Denmark with local market prices being higher than that of Norway. At the same time the Danish scope for development in its own marine zone is limited due to the suitability analysis. Therefore, Denmark in the NORD union case has access to Norway's marine zone site can deliver low cost renewable energy into the energy mix. All the partnerships are shown to be highly beneficial except for marginal decreases for Norway and Portugal by just under 1%. This is due to the one partner nation accessing more sites for development. Similar results are seen in the wind modelling outcomes.

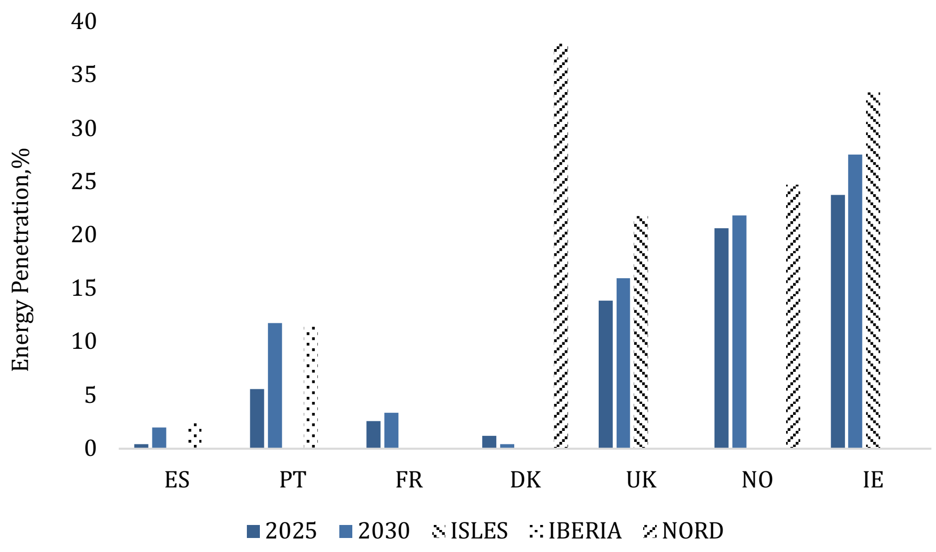


Figure 97. National energy mix penetration of floating wind for the models considered. Where, ISLES = UK + IE, IBERIA = PT + ES, NORD = NO + DK.

The floating wind energy penetration levels are observed to be significantly higher than wave for all countries with a mean wind penetration of 11.8% and 3.3% for wave. This is especially true for the UK, Norway and Ireland, all showing levels over 15% and Portugal up to 12% of the national energy mix. This is in part due to the reduction in cost of the technology in the solver model but also the reduced variability seen in the energy production. However, Spain, France and Denmark have comparatively limited penetration levels. A benefit of development partnerships is observed for each of the wind cases with Denmark and Ireland potentially being able to achieve approximately 35% national energy penetration. This is again attributed to the access of low cost sites for development found in their partner nation's marine zones and their energy mix demand for cheaper renewables. Conversely, Spain and Portugal still do not reach higher than slightly above the 2030 levels of penetration. This is again attributed to the out competition of the two partner nations operating with limited sites available. When considering these results in the broader context of this work, the relationship between the allocated capacities and the market modelling can be seen. Table 39 demonstrates the relationship between the two modelling processes.

Table 39. 2030GW installed capacity allocation connection results and Genetic Algorithm, (GA) penetration results.

	Wind		Wave	
	GA	Allocation	GA	Allocation
ES	0.7	8.8	0.2	3.2
PT	0.9	11	0.3	3.8
FR	2.1	10	0.8	8
DK	0.2	0.3	0.3	0.6
DE	0	0	0	0
NL	0	0	0	0
BE	0	0	0	0
UK	5.1	20.5	1.3	10
NO	3.6	15.4	0.8	9.6
IE	1	4.1	0.2	1.8

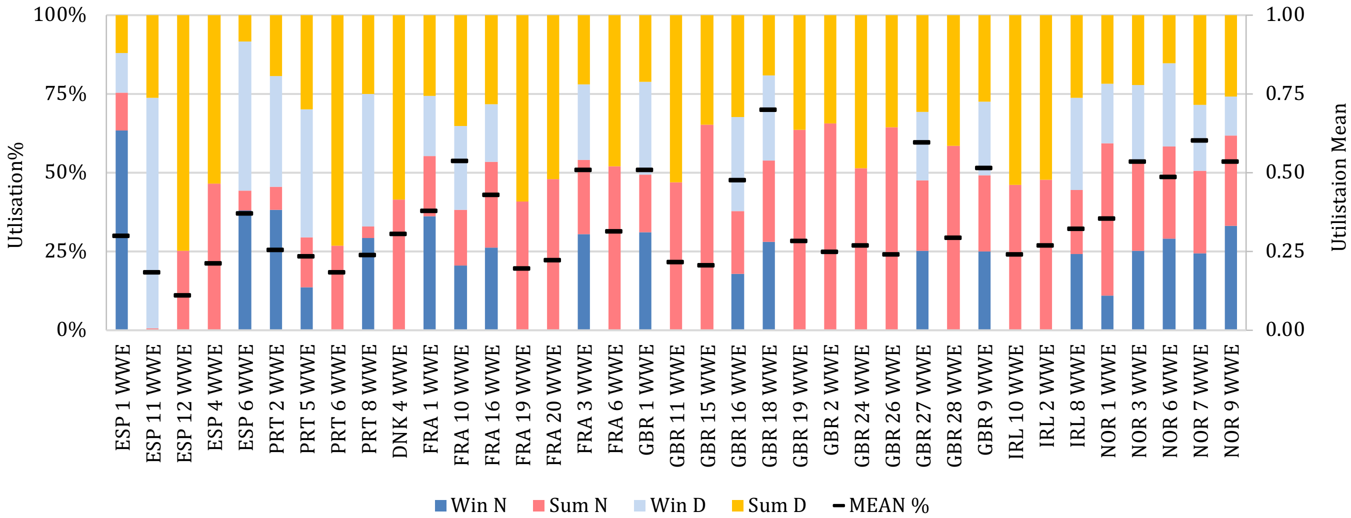
The energy penetration level was recorded to be on average 19% and 10% of the allocated capacity for wind and wave respectively. This demonstrates how significant the wider market forces considered are in infrastructure assessments for the industry. The regional transfer capacity established in the grid assessment in section 7.4.1 demonstrated the relative strength and capacity of the grid to the coastal nodes. In many cases the grid strongest regions are located in central regions and not the coast. With Ireland, the UK, Norway and France all demonstrating this pattern. However, Portugal Spain and Denmark have the highest grid strength along the coastal regions and the poorest floating WWE penetration.

When considering these results in the broader context of research in the field, common themes of similarity were identified. The EU commissions market study on ocean energy in 2018 [173] highlighted that 0.5GW of capacity could be achieved for wave energy between 2020 and 2030. Although this did not consider the sites available in Norway and this figure is low in contrast with the outputs of this thesis. However, these figures are highly variable across literature and the EU commissions report [174] demonstrated that 16GW capacity by could be achieved by 2030. While it must be said these values do not take into account the same level of analysis conducted in this thesis, the output of 3.9GW capacity lies between the two values outlined in literature. A Spatially relative study conducted for the UK using an energy systems model [37] identified a potential in 2050 of 4.9GW of wave energy capacity. This figure falls in line with the penetration results identified in this work. The results for floating wind showed further alignment with current research. The European association for the wind industry, Wind Europe, outlines in a market status report that 4GW of floating wind capacity could be achieved by 2030 [175].

The work in this thesis estimated that 28% of the transfer capacity in Europe is located in the Iberian Peninsula with 30% and 87% grid capacity connected to the coast in Spain and Portugal Respectively. While Denmark maintains almost 35% of the grid capacity at the coastal nodes it has significantly less development sites compared to Spain and Portugal. Therefore, the assumption can be drawn that although coastal transfer capacity has an impact on the volume connected it is not the most significant factor in floating WWE connection. This is in part due to the reduction in cost of the technology in the solver model but also the reduced variability seen in the energy production. Therefore, in order to maximise the success of floating development sites understanding how these relationships influence the sites and capacity installed must be examined.

8.4.3 Temporal Profile

The constituent time frames that form temporal profile in this work are the mean values for winter and summer day and night. In order to demonstrate how this underlying factor is impacting penetration this section demonstrates the outputs for each node at each time frame for two scenarios 2025 and 2030. The genetic solver sought to identify the minimum cost of generation for each coastal node subject to constraints as discussed in 7.8. This analysis not only considered the inclusion of floating WWE but also the temporal variation seen with such systems and energy sources. The significance of addressing temporally fine data rather than an annual mean is reflected by the relationships of demand patterns and intermittent production. The solver model outputs seen in Figure 98 and Figure 99 for wave and wind energy respectively highlight the result of variability for each of the coastal regions with WWE connections.



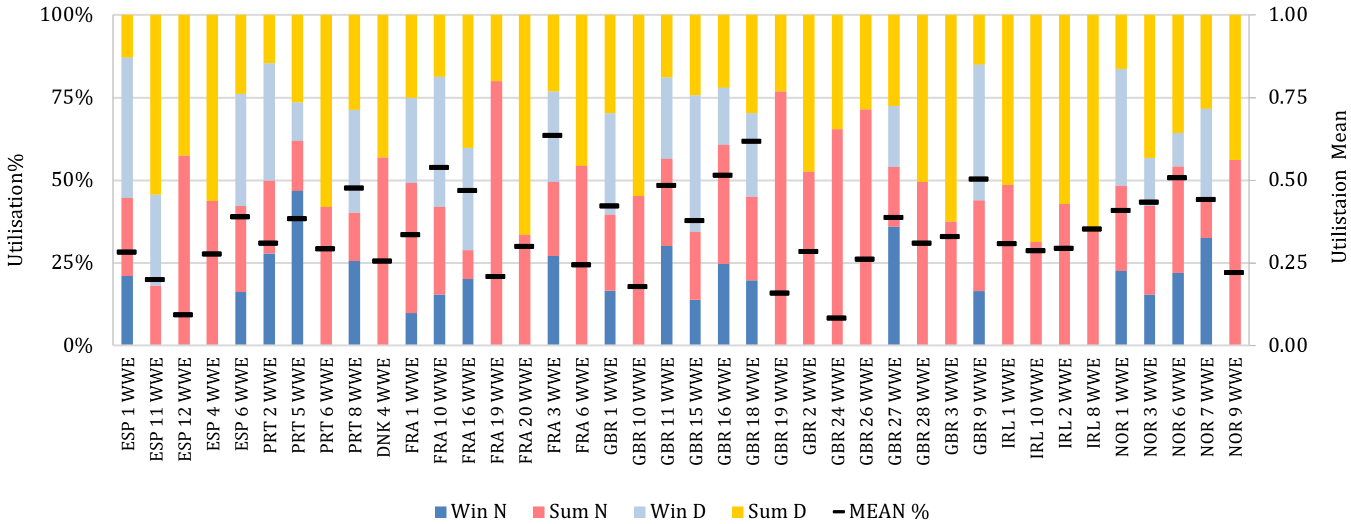


Figure 98. Temporal wave energy utilisation from potential MW output for 2025 (top) and 2030 (bottom). Nodal subregions are subdivided by country code where: ES=ESP, PT=PRT, NK=DNK, FRA=FR, UK=GBR, IE=IRL, NO=NOR.

The outputs for wave energy utilisation across both scenarios demonstrate the dominance of some regions over others. The ideal temporal profile would have winter and summer values with even utilisation and a high mean value. This pattern is observed in several instances in 2025 with GBR 9/18/27, FRA 10/3 and all of the NOR regions. These demonstrate the most suitable locations for the technology. While the worst performing could be identified as example, ESP 11/24 and PRT 5/6. It was identified that Nodes with increasing levels of solar generation such as Spain and Portugal demonstrated a significantly lower utilisation profile and, in some cases, reversed. This is not only due to the demand profile but also the use of large volumes of solar generation in summer and the summer floating wave production profile. Similar trends are seen in the 2030 scenario with an overall increase in utilisation from a mean 0.3% in 2025 to 0.35%

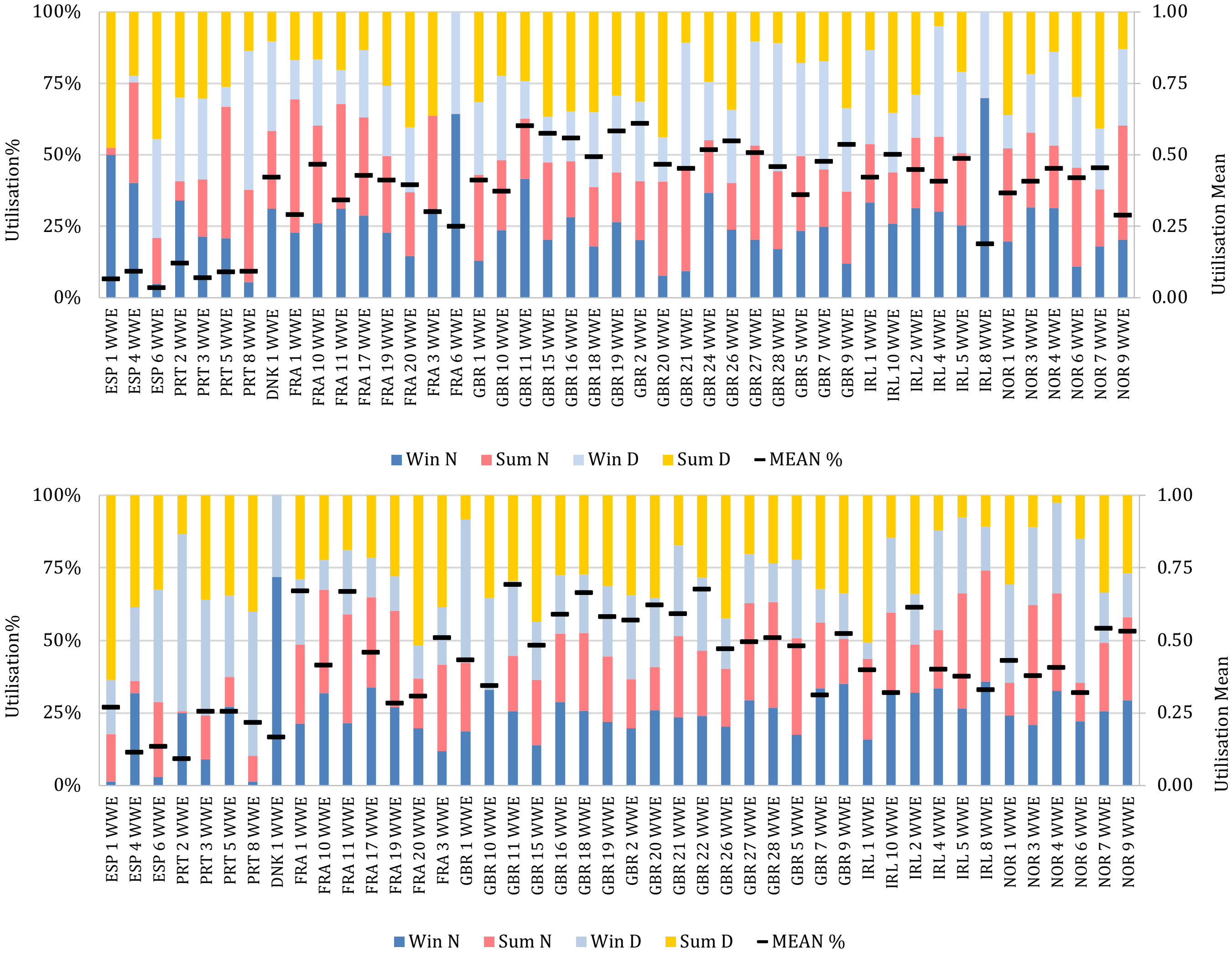


Figure 99. Temporal wind energy utilisation from potential MW output for 2025 (top) and 2030 (bottom). Nodal subregions are subdivided by country code where: ES=ESP, PT=PRT, NK=DNK, FRA=FR, UK=GBR, IE=IRL, NO=NOR.

In contrast to wave a more distinct pattern can be observed in the utilisation of wind. With a larger number of regions being more suited due to the less extreme variability of wind power production, as explained in section, 4.7. Between the two technologies this difference in utilisation has wind being 8% and 10% higher for 2025 and 2030. Nodes with increasing levels of solar generation such as Spain and Portugal demonstrated a significantly lower utilisation profile and, in some cases, reversed. This is not only due to the demand profile but also the use of large volumes of solar generation in summer. The oversupply of renewable generation is apparent in other regions that do not share the same demand or production profiles. In the floating wind model the Danish node DNK 1 performs much worse in 2030 than 2025. This is attributed to the oversupply of fast growing and cheaper renewables already under development taking over the room for deployment. The mean utilisation across each of the nodes in the wind model are, as expected, higher than wave with 0.38 (2025) 0.45 (2030).

8.4.4 Development Time Frame

The previous results highlight how floating wind could become a major part of the energy mix in Western Europe. However, the manufacturing of this level of new development could be time consuming. Therefore, understanding the time to roll out such volumes was addressed in the port analysis. In order to make the correct relationship the sites were re-allocated port facilities. This involved assigning the volume connected to the grid to suitable port locations. The MW capacity for each grid connection node was assigned a LCOE value and cell site id through the analysis which was used in the re allocation. This process is significant as varying volumes of power will be connected after the energy mix assessment. The output of the port re allocation provides an approximated distance for which port analysis could be conducted. The resulting time to roll out and volume of devices to be serviced, this is demonstrated in Figure 100.

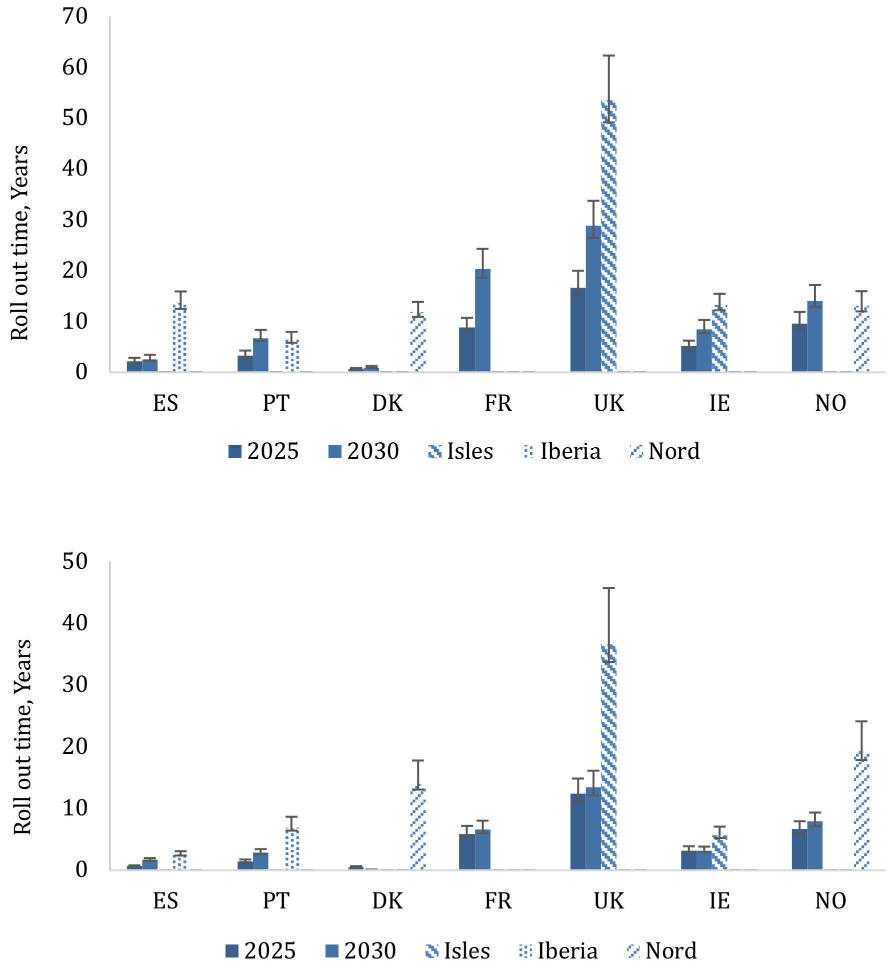


Figure 100. Roll out time for floating wind. Where, ISLES = UK + IE, IBERIA = PT + ES, NORD = NO + DK.. While the range of outputs includes a margin of error.

The two graphs outline the time to develop the WWE potential identified in the energy mix model. Although a margin of error was present in the model outputs the trend of development is maintained with errors increasing over time as shown with the UK and Norway. However, for Norway and Ireland to achieve an approximated 20% floating wind mix by 2030 remains achievable under 10 years of development. For UK example, in order to achieve the 2030 total, roll out of the 17% floating wind possible in the UK's energy mix approximately 37 years would be required with current port infrastructure. However, to develop the levels of power in the ISLES model the UK and Ireland do not have the port facilities to achieve deployment without significant time delays. Relationships of development size and roll out time are represented in Figure 102 for two scenarios. The optimum relationship being maximum capacity and minimum roll out time, the upper left quadrant as outlined in Figure 101.

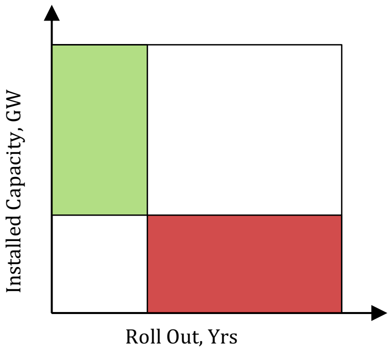


Figure 101. Demonstrative time for development plot, where the most suitable outcome would be the green zone and worst the red zone.

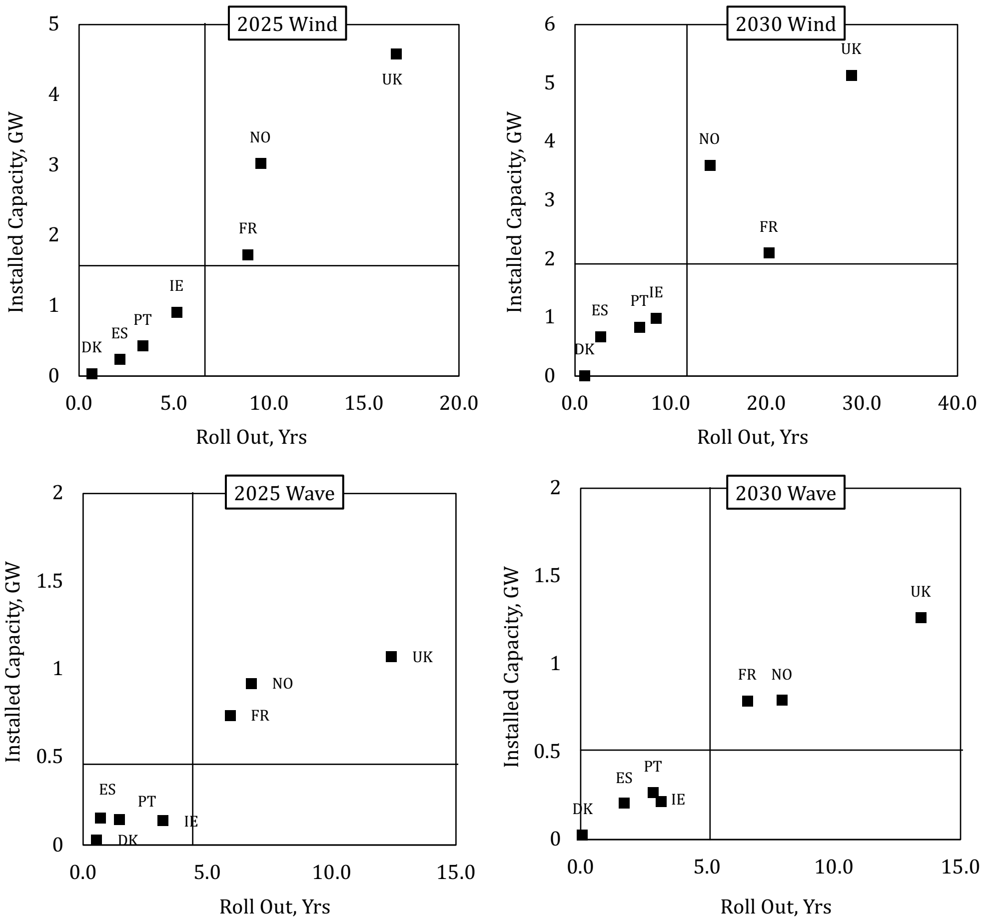


Figure 102. Installed capacity and roll out time for both technologies in 2025 and 2030.

In the 2025 model for wind the most suited roll out for capacity is observed to be France and Norway. However, this changes when considering the 2030 scenario. Where the roll out time for France increases rapidly with minimal capacity growth. Ireland, however, performs reasonably for the wind installed capacity but poorly for wave. The study countries demonstrate a significant shift, nearly double, the roll out time for a limited increase installed capacity, 11GW to 13.4GW.

This demonstrates that development past 2025 would be unsuitable with current port infrastructure. Across all countries this is attributed to the two technologies port requirements. Although having more suitable ports and having lower restrictions in operability of vessels, the wave technology still remains slower to develop and at a lower penetration level over all national mixtures. This is due to the number of devices required to produce such high volumes of power. In the context of the field of offshore renewables the time frame to develop large volumes of power can be related to the offshore wind industry. The Renewable UK report on offshore wind project timelines [176] demonstrated that over a 12 year period from 2018 to 2030 the industry seeks to deploy 17GW of capacity. While this work demonstrated that in a snapshot at 2030 developing 5GW of floating wind capacity could take up to 17 years. Although this is a higher value, the offshore wind industry is significantly more advanced with its development and support systems and will naturally be faster to roll out.

Key Findings: Research Question five was drawn out over two analytical processes to explore roll of location and capability on the capacity and cost available for connection and servicing. This relationship is presented in Table 40 as a summary of how capability impacts capacity and floating technology deployment.

Table 40. Research Question 5 summary of findings for 2030 capacity installed.

	Installed Capacity, GW		LCOE, £/MWh	
Technology	Allocation	GA	Allocation	GA
Wave	**37**	**3.9**	**118**	**112**
Wind	**70**	**13.6**	**97**	**94**

The impact of infrastructure capability on the outcome of the 2030 model demonstrates a significant reduction in capacity. With wind energy connected capacity being four times higher than wave this demonstrates that a larger market could be available for the technology. The LCOE reflects how the market model in the GA has impacted on the sites available for deployment when compared to the allocation model. While not extreme with variation observed at 5% for wave and 3% for wind. The output of utilising Energy partnerships was found to be of significance for 3 main groups as identified in allocation modelling. These include IBERIA (Spain and Portugal), ISLES (The UK and Ireland) and NORD (Norway and Denmark). Table 41 outlines the findings of these combined outputs in relation to the energy penetration mix.

Table 41. Research Question 5 summary of findings for percentage increase from national mix to Energy partnerships mix.

	Increase from National 2030 Energy mix percentages		
Technology	ISLES	IBERIA	NORD
Wave	**2.0**	**0.4**	**11.6**
Wind	**11.7**	**0.2**	**40.8**

What is demonstrated is an increase for each of the scenarios considered. With Norway and Denmark demonstrating the largest increase for both wave and wind technologies from the combined national mix. These results demonstrate the advantage of using policy in both grid strategy and marine management to achieve energy targets. The average time taken to develop the capacities observed in the Western Europe 2030 model are presented in Table 42.

Table 42. Research Question 5 summary of findings for 2030 roll out time.

Technology	Average Time for Deployment, year
Wave	**5.1**
Wind	**11.7**

The findings presented demonstrate that although four times fewer GW's of capacity can be installed for wave, but it could take less time to deploy. This demonstrates that floating wind would be more viable with meeting larger targets but requires increase port strategy.

8.4.5 Floating Energy Development Strategy

Through the combining of analytical methods and the results discussed in the preceding section an assessment can be made into the most cost-effective development plans for the technology considered. The final set of results demonstrated is a distribution of sites suitable of strategic development in Western Europe, this question was defined as:

6. Where are the optimum sites for strategic development and where should infrastructure be developed to satisfy the needs of developments?

Although the outcomes of site suitability are dependent on the infrastructure variables being considered, a series of strategies for site development have been proposed. The sites evaluated are assigned scores for the associated infrastructure required. Port ratios sub 1 are considered adequate with ratios between 1-2 being adequate at an ability to build around a 2-4 year development plan. Above 2, would be considered poor and require further assessment. For the grid the ratio of inclusion was used to represent the viability of a site. The seasonal inclusion value, a mean level across the time frames was used for each site. Those sites which could be connected and produce stable power over the year are considered to be most viable with those with minimal inclusion scoring worse. A mean inclusion value of over 50% was considered to be suitable with below 40% unsuitable. Utilising the infrastructure outlined in the previous section, the final sites identified throughout the selection process have been categorised into four of development stages based on the thresholds set, defined as:

1. Adequate facilities, both port and grid levels score in the top threshold.

2. Some Consideration, one or both of the infrastructure types are approaching the scoring thresholds.

3. Requires action, either port or grid is inadequate and is in breach of the threshold limit

4. Currently Unsuitable, both infrastructure types are inadequate in the current state.

These rankings have been chosen to reflect that although these sites have proven to be possible in analysis, they are not all ranked with the same level suitability. The output of this classification is represented in Figure 103 for the 2030 model.

Figure 103. Strategic development sites for 2030 with wind stages (left) and wave stages (right) with a higher number of wind development sites represented.

When considering the two technologies the total volume of connected wind is higher than wave with 13.6GW compared to 3.9GW. From these outputs it could be suggested that wind is more poised to make larger scale array developments than wave energy for this infrastructure model. For floating wind, the UK maintains the best groupings of sites for the infrastructure considered with Norway also having a large number of sites. While France has a limited grouping of suitable deployment stage sites. Although the coasts of Ireland and Portugal demonstrated suitability in previous results sections, they are both limited by the infrastructure available. A similar distribution is observed in the wave case with the south coast of Ireland and the UK and

France having the best groupings of sites. While Norway maintains a grouping of wave sites it is not to the same extent as that for wind. Portugal, Spain and Denmark perform badly in both cases and would therefore be most suitable for further investigation into infrastructure capability. The Western European outlook for deployment and associated infrastructure suitability is demonstrated in Figure 104.

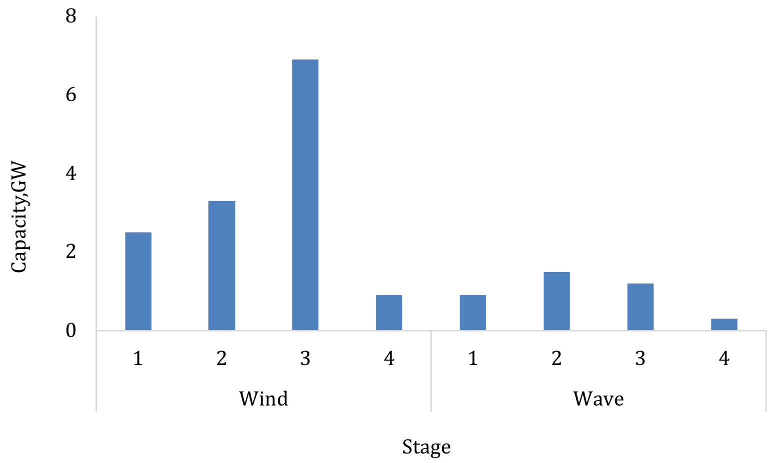


Figure 104. Stages of development and the associated infrastructure suitability for wind and wave. With wind values of 1) 2.5GW (18%), 2) 3.3GW (24%), 3) 6.9GW (51%), 4) 0.9GW (6%). Wave values of: (right) 1) 0.9GW (23%), 2) 1.5GW (34%), 3) 1.2GW (34%), 4) 0.3GW (8%).

What is observed is that the sites suitable for development do fall into similar distributions between technologies with majority of sites requiring further investigation. While Wind technology has an increase in suitability based on infrastructure capabilities considered.

8.4.6 The European Context

The final research question explores how infrastructure development might impact the optimum deployment. Stage 1 and 2 sites represent what could be deployed at minimal hindrance. The key finding in relation to these sites is presented in Table 43.

Table 43. Research Question 6 summary of findings for 2030 demonstrating the installed capacity and associated site annual power generation possible for stages 1 and 2.

Technology	Installed Capacity (GW)	Generation (TWh)
Wind	5.8	22.9
Wave	2.4	3.2

The wind outcome of this work falls in line with the studies into a potential market deployment of 6W in Europe from [177]. While this thesis has also found that a remaining 7.8GW of capacity would require further development and investigation. The wave value is closer to the estimates seen in the EU commission report on ocean energy being able to cumulatively deploy 2.1GW [173]. The potential for wind capacity is increased by the technology's lower temporal variability in generation, which impacts the energy market model leading to a significantly lower generation output against a relatively measured difference in installed capacity. The generation output is significantly lower than the raw costed potential identified before infrastructure modelling, Table 34, which was estimated at 806TWh and 1667TWh for wave and wind respectively. While the target of the EU to achieve over 32% renewable generation by 2030 is underway, as of 2018 only 19% of that target had been met. The previous results of the allocation modelling prior to the energy market model demonstrated that significantly higher levels of power generation could be achieved. The allocation model highlighted 37GW for wave and 70GW for wind with a corresponding annual generation output of 55TWh and 292TWh. This would represent 1.7% and 9% for wave and wind respectively of the European annual power demand at 3200TWh for 2018 [8]. This outcome demonstrates that in the context of European energy requirements, floating wind and wave technologies could be delivered economically by 2030 and contribute meaningful volumes of renewable electricity.

The thresholds discussed throughout this work all influence capacity. However, the infrastructure capability assumptions have demonstrated the most significant impact. As was seen in the allocation modelling the coverage ratios for 2030 highlighted that the grid was twice as likely to reduce capacity. While the results in the market mix modelling demonstrated that it is variability of generation and access to demand that would impact power more. Energy market modelling highlighted that 90% and 80% for wave and wind of allocated capacity were reduced due to the lack of access to demand or seasonal variability. Possible expansions to the work into the field of the thresholds set in this work are explained at length in further work section 10.2. This chapter section considers the scope for new applications as well as addressing the aforementioned issues.

8.4.7 Infrastructure Targeting

In order to target infrastructure development, the understanding of the core factors driving such suitability were evaluated. The sensitivity analysis in section 7.7.6 did show that an increase in capacity led to more connection. However, what has been observed is that the wider energy market forces have a larger impact on the siting of arrays and relative capacity of the grid. The suitability of regional grid infrastructure developments is therefore an amalgamation of both of these two factors. Therefore, this section demonstrates how this thesis could be used to focus the direction of research into grid infrastructure support for the industry.

Through using a ratio of volume connected and volume potential the relative regional grid infrastructure strength can be examined. Similar can be assessed for the port infrastructure. Ports that are most suitable but are unable to process the volumes required for its region can be evaluated. A ratio of connected array volumes and the build time frame can be used to determine which ports require further attention to support the industry. Ultimately the selection of sites and allocation of infrastructure is dependent on the desired volume of WWE to be developed. As discussed, the genetic algorithm considered the most feasible amount of WWE to be included in 30% renewables by 2030 energy mix target. With both industries currently at pre commercial scale the volume of power to be connected are relatively large and naturally if WWE connection were lowered there would be a divergence in coverage for both ports and the grid. However, 'maximum achievable' cases are considered in this work**.** The infrastructure suitability for 2030 of both port and grid capabilities are demonstrated in Figure 105 and Figure 106 for the technologies considered. The figures demonstrate the adequacy of the infrastructure for the constraints set in the models.

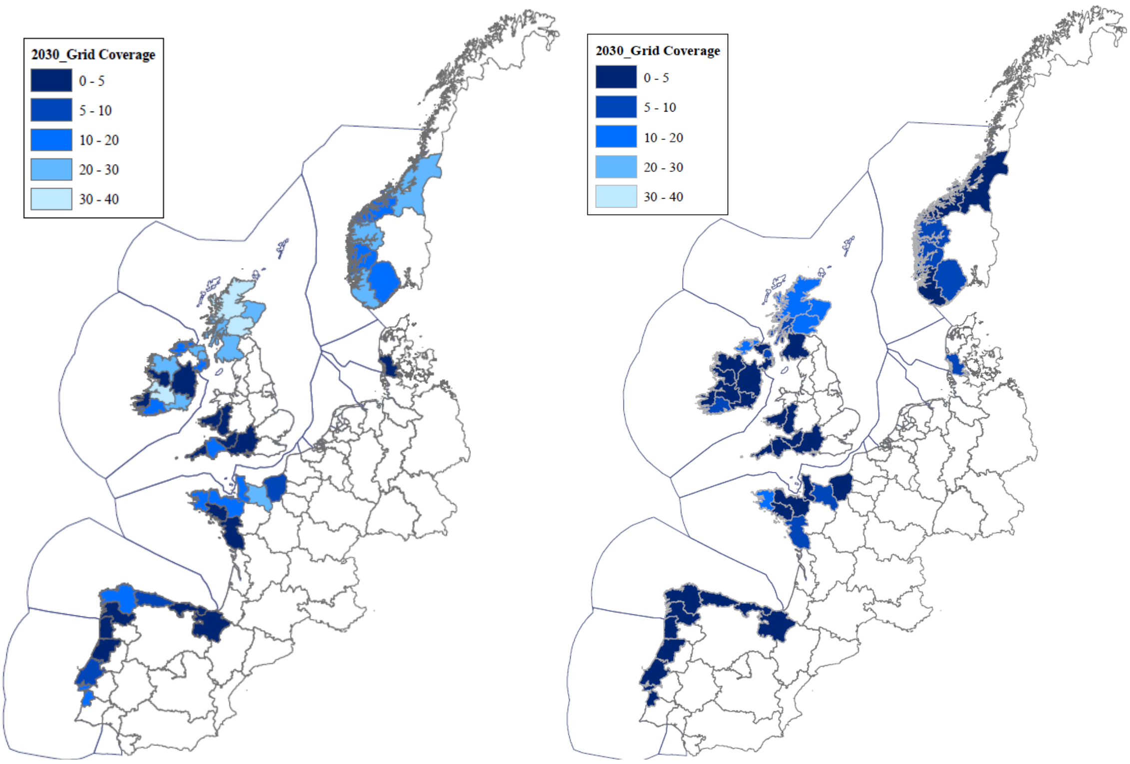


Figure 105. Grid infrastructure coverage for wind (left) and wave (right) in the 2030 scenario.

The most suitable grid coverage is observed to be on the northern coasts of Ireland and Scotland while above average coverage is observed in Norway and Northern France. The poorest coverage regions demonstrate how the grid is unable to match potential. This lack of coverage is most evident around Spain and Portugal as well as the south of the UK and parts of Ireland and France. When discussing the challenges facing the requirements for grid coverage it cannot simply be assumed that increasing hosting capacity will directly have a positive impact on sites and coverage volume. As has been discussed seasonal variability plays a major part in the suitability of the grid. However, this work could be expanded to allow the grid solver model to breach the line restriction when needed to maximise wave and wind energy potential connection. By doing so, regions with a breach, would indicate a suitable capacity and location for maximised upgrade impact for the technology. However, the coverage results have been used as an indication to suggest regions that could benefit from either port or grid support in the form of more detailed planning analysis, investment and/or research.

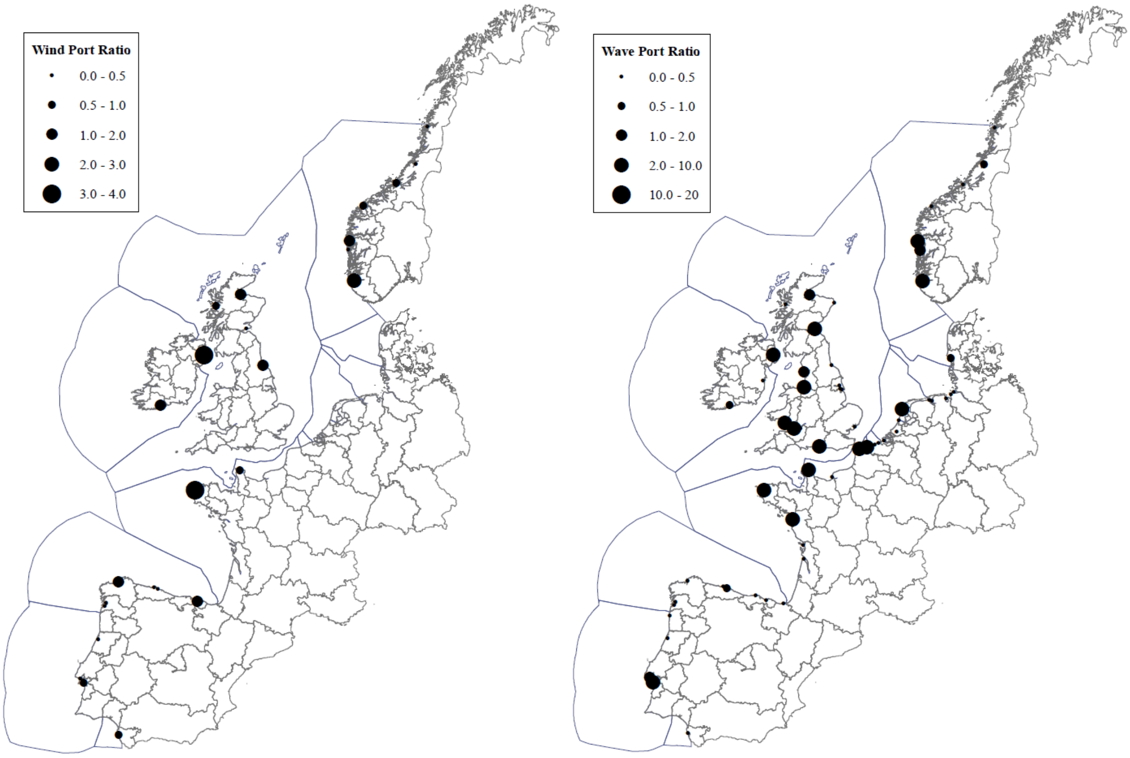


Figure 106. Port infrastructure coverage for wind (left) and wave (right) in the 2030 scenario.

The wind port coverage is best in, Northern Ireland, North West France, Scotland and the southern ports of Norway. The wave port infrastructure coverage distribution is a more concentrated around the UK, northwest France sand southern Norway. What is seen is the increased use of a larger variety of ports due to the lower wave technology restrictions. The Portuguese coast has poor port facilities, and this would indicate that ports in the surrounding area could benefit from further investigation. Furthermore, the research highlights that owing to the more stringent restriction imposed by the wind technology, exploring the impact of floating wind technology types would be useful, this is outlined in the further work section 10.2.1.

8.5 Chapter Summary

Results from each of the modelling steps have been presented in this chapter to answer each of the research questions in succession. The three stages of site suitability have been addressed with the first set of results of basic site potential outlines for the work conducted in chapters 3–5. The second analytical method of addressing the allocation of infrastructure and the cost associated with developing floating wave and wind technology is demonstrated for various case studies. The final results section of the infrastructure analysis is also demonstrated.

9. CONCLUSIONS

9.1 Summary & Conclusions

Western Europe is continuing on a path of power sector decarbonisation and is looking to generate increasing levels of clean, cost-effective electricity. This thesis presents a method to evaluate where floating wave and wind energy (WWE) might be used to produce large scale clean energy in Western Europe. The problem of connecting large volumes of power, installing and supporting developments is an issue that must be addressed far in advance of technology roll out. After reviewing literature, it was identified that such high level investigations into infrastructure specifically targeted to floating WWE development was lacking. The gaps in the literature led to the creation of 6 research questions that this work has answered.

1. What is the impact on sites for industry development taking into account mooring suitability?
2. Where are the optimum deployment areas from a resource perspective?
3. Considering other marine stakeholders where are the optimum sites from a marine spatial planning perspective?
4. Does existing port and grid infrastructure affect the selection of sites for exploitation?
5. How would infrastructure capability changes alter the overall deployment areas and associated costs?
6. Where are the optimum sites for strategic development and where should infrastructure be developed to satisfy the needs of developments?

9.1.1 Approach

In order to simplify the assessment the models were based around two technology types to reflect the floating wave and wind industries, as well as fixed port and electrical infrastructure configurations. Furthermore, the outcomes were addressed as a series of hypothetical strategic development scenarios based on the most up to date and available data. Due to the scope of work being aimed at such a large geopolitical area encompassing multiple nations, not all of which are EU member states, considerable effort was made to create robust datasets to perform analysis. This thesis utilised the most relevant data available and while it is understood that new information may change results by creating a series of development scenarios, the models demonstrate a relationship between cost, infrastructure and policy strategy. By targeting key areas, the models highlighted the most beneficial areas for focused development and where expanded understanding was required.

In the literature review, existing tools for the assessment of each of the research questions was presented and discussed, however, there were no unifying methods that assess all the topics covered in this work. Further, there was little focus to the bespoke needs of the floating industry. To answer the research questions, an approach was taken based around a spatial analytical model established in software ARC GIS. The software was used to create a spatial analytical system capable of conducting multi-level analysis on technical, economic and geographical datasets. This was used to assess the impact of marine spatial planning and marine management on site selection. This primary output was used as a basic site suitability to be developed upon with subsequent models.

After this primary stage, cost and infrastructure relationships were explored in a series of spatial analytical algorithms designed to allocate suitable numbers of arrays to infrastructure locations. This model considered the theoretical hosting capacity of both ports and the grid at a coastal grid connection level over an annual mean. The port being a static estimation of the number of devices serviceable in a year and the grid an amalgamation of demand and transmission capability. The outputs of which were used to determine the suitability of infrastructure and impacts on cost. This relationship created the second stage of site suitability. However, for both infrastructure types this output was observed as being too static. These types of analysis have been conducted in the past as was observed in the literature.

Previously developed tools have often omitted many practical constraints and considerations significant to the understanding of infrastructure suitability. Therefore, a second analytical process was established to explore the more practical assessment and thereby reduce uncertainty. Modelling was conducted to assess the issues of connectivity into the wider energy market considering: cost of generation, temporal variability for demand and all generation considering all plant over 10MW, the energy mix targets, minimum stable generation and transfer capability in the system. A genetic algorithm was developed to explore the penetration levels of floating WWE considering these forces. A Further, port assessment process was then established to re-evaluate the roll out of the potentially connectable volumes of power. The port analysis considered the more practical constraints effecting roll out, including time to site, operation window, time in port and the space in port for multiple operations. Applying these metrics provided an insight into how regions and/or ports could be evaluated for their suitability.

Using these methods, this thesis assessed the infrastructure effecting development and outcomes used to formulate an outline for a development strategy. This sought to identify the strategic development of the supporting infrastructure for floating wave and wind technology and what sites might be considered most suitable for deployment.

9.1.2 Key Findings

After applying the analytical techniques to each of the research questions, results demonstrated that floating wave and wind energy on a large scale does have potential for development. Although tailored to the two technology types, the work could be expanded to include multiple types of devices.

The first research question, involving mooring suitability, demonstrated how basic technology limitations have an impact on location. These results showed that not all countries in Western Europe would be suitable for the technology and the average remaining marine area was observed to be 41% and 20%, representing a total remaining area of 913886km^2 and 802609km^2 for wave and wind respectively. If the entirety of this area were to be utilised for development of floating technology, up to 45TW and 13TW could be available for wave and wind. The second research question focussing on power production demonstrated that not all sites within the remaining sea zone could be considered suitable for deployment. These key findings showed that a mean annual energy production per cell of 2km^2 of 12.5GWh and 17.5GWh could be available for wave and wind technologies. A range of capacity factors were estimated across the remaining study area with the top 90 percentile of sites to be approximately 30%, with the mean being 15%. Wind capacity factors were shown to be significantly higher with approximated mean values of 53% and 63% in the top 90 percentile. It is important to note that the capacity factor average for onshore wind turbines in the UK known to be at a mean of 25%. This comparison indicates the benefits of locating technologies to higher quality resources. The results demonstrated that wind energy might have a higher average power production for the marine area considered.

Within this area the mooring suitability, energy production and marine stakeholder assessment formed the basic sites suitability with hot spot groupings identified for development on a large scale. From the remaining sea space identified in research question one, an average of 15% and 16% representing 298661km^2 and 263105km^2 were found to be suitable for wave and wind respectively equating to approximately 15TW and 4.2TW of installable capacity. The findings show that large areas of the marine zone were lost to marine spatial suitability. The results also demonstrated a more focused scoring for wave technologies and a larger range of sites being suitable for floating wind. This outcome formed the regions of the basic site suitability and foundation for following modelling work.

The relationship of cost and infrastructure was demonstrated through the answering of the fourth research question. It was found that the technology would not be able to compete at a comparative £100/MWh until 2025 considering the optimum or unconstrained scenario for infrastructure. By 2030 the models highlighted that 36%, 107518km^2, of the remaining marine zone was suitable for wave technology and 88%, 231532km^2, for floating wind. Up until this research, focus area wave had a large scope for deployment, however a new total of 5.3TW and

3.7TW of respective wave and wind capacity was identified. When drawing a contrast between the two technologies it can be determined that floating wind has larger scope for deployment in terms of cost. However, the wave energy market remains a significant portion of the remaining sea zone.

The relationship of infrastructure was further explored in the spatial and genetic algorithm market model. Research question five was drawn out over these two analytical processes to explore the role of location and capability on the capacity and cost available for connection. For allocation modelling the two forecasts of 2018 and 2030 showed increases in potential capacity for wind from, 65GW (2018) to 75GW (2030). Comparatively the change in wave potential capacity was limited to 35GW (2018) and 38GW (2030). This would also indicate that the small growth in infrastructure development being planned would have an impact on deployment levels. The impact of international development partnerships was observed to be highly beneficial for 3 groups, NORD (Norway-Denmark), IBERIA (Spain-Portugal) and ISLES (Ireland-The United Kingdom). With the ability to build in partner's marine zone and connected to either grid the exploitation of larger numbers of low-cost sites was seen. Although suitable for an annual overview, the application of a static value for ports and the grid were observed to be insufficient for assessing the technology. The energy mix percentage, through utilising energy partnerships, demonstrated increases for each of the three case studies. With Denmark and Norway showing the largest gains, with floating wind and wave providing an increased 40.8% and 11.6% of the total energy mix.

Detailed analysis, utilising operations modelling for ports and a genetic algorithmic market model for the grid, observed the more practical limits of deployment and were observed to be significantly lower than the allocation model. It demonstrated that 3.9GW for wave could be deployed at an average LCOE of £112/MWh against 37GW of potential. While for wind similar findings demonstrated that 70GW could be allocated compared to 13.6GW in the market model at average LCOE values of £97/MWh. The allocation model highlighted 37GW for wave and 70GW for wind with an approximate annual generation output of 55TWh and 292TWh. In the context of the European power demand of 3200TWh, annually this would represent 1.7% and 9% of the total for wave and wind receptivity. However, modelling showed only 3.9GW of wave and 13.6GW of wind from the allocated capacity could be utilised effectively. Therefore, the infrastructure capability assumptions and thresholds have demonstrated the most significant impact. Energy market modelling highlighted that 90% and 80% for wave and wind of allocated capacity were reduced due to the lack of access to demand or variability. Furthermore, allocation modelling demonstrated that coverage ratios for 2030 highlighted that the grid was twice as likely to reduce capacity, although impacts were location specific.

While it was observed in allocation modelling that increasing regional capacity for ports and the grid can increase installed capacity, it was also found that focussing attention on current sites and infrastructure could be highly effective. This was further demonstrated in the secondary analysis. The final set of results outlined a guide to strategic development considering the infrastructure capabilities. The total capacity that could be supported requiring limited or no improvement was observed to be 2.4GW for wave and 5.8GW for wind. While a remaining 7.8GW of floating wind and 1.5GW of floating wave could be deployed but might require targeted assessment or improvements. This final outcome resolved research question 6 and the relationship of infrastructure and deployment. A demonstrative overview of how this work could be used to target infrastructure was established and those sites that require further assessment were outlined. Considering these approaches, rather than embark on large and expensive building plans, several focused efforts tailored to the requirements of the industry could be deemed more effective in supporting the industry.

With these two technologies being relatively nascent in terms of utility scale energy production, it is imperative that policy makers best utilise all tools available to allow decision making to be more proactive and pre-emptively address issues. While this work has demonstrated the combination of modelling approaches that can be used to identify development potential, it is up to the policy maker to utilise these types of tools to evaluate infrastructure requirements. This work highlighted that grid infrastructure is the most restricting factor, blocking mass adoption of potentially cost-effective floating wind and wave technology. Therefore, policy makers should utilise this understanding to then evaluate electrical infrastructure in more detail.

10. Further Work Recommendations

10.1 Methods

The work presented in this thesis has explored the methods used to set out infrastructure development plans for floating wave and wind energy. Furthermore, this work has drawn conclusions using assumptions to explore relationships, however, there are a number of improvements which could be made to expand the understanding but also reduce unknown factors that may have an impact on, performance, site suitability, allocation modelling, cost estimation and infrastructure development.

10.1.1 Array Density & Wake Loss

Wake losses were calculated for the reduction in performance due to the prevailing direction of the resource relative to the array. The density of devices within an array was assumed from known commercial configurations in the case of wind and in the case of wave technology estimated from research. However, a sensitivity analysis could be conducted to explore the variability in production due to energy absorption and the impact this might have on arrays in the lee.

10.1.2 Mooring Loading Analysis

An analysis into the mooring limitations of the technology and its station keeping could be expanded upon. The work presented utilised hindcast met-ocean data to establish performance. What is also presented is the mooring conditions found across the study area. The combination of these two data sets and the structural properties of the spar buoy and heaving point absorber could be combined to estimate the maximum safe loading for the technology. This may have an impact on the suitability of sites particularly those in exposed North Atlantic conditions. A brief overview of the proposed method to establish a spatial constraints map is presented as follows. Figure 107 demonstrates the approximated mooring line characteristics that could be examined to provide both a better estimate of cost and also an estimate to loading suitability.

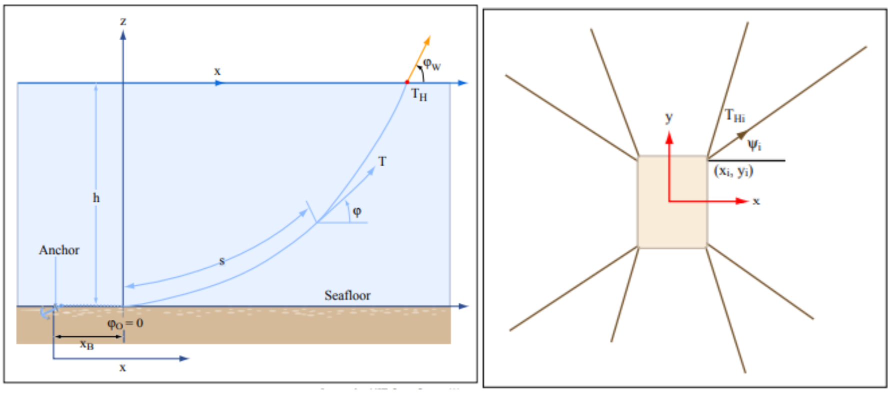


Figure 107. Multipoint mooring loading static analysis demonstrating two assessments for single line load conditions, left, and multi point load conditions, right. Load conditions are subject to the drag caused by lateral loading on anchor chains creating the vectors y and x [178].

Combining the mean lateral loading of wind, tide and wave directional forces over would provide a lateral force vector which could be assessed. The depth to sea floor would determine the footprint and length of material required. Designing for a limited deviation from start position would provide the maximum combined loading for the multipoint mooring within 45-degree bins. Combining the mean directional load with the depth and length of material would allow for an assessment to potential limits of strength against cost. Assuming that the lowest cost option is preferable a limit to combined environmental loading could be estimated and mapped. Therefor demonstrating suitability and increased understanding of mooring cost.

10.1.3 Cost Path Networks

Allocation modelling determined the cost path matrix from which estimations over distance where derived. However, using a fixed square matrix contains limitations due to the cost path analysis only choosing x and y vectors at 90 degrees. A hexagonal network is known to provide greater representation in cost path analysis due to the use of more routes and ability to move in more degrees. Figure 108 demonstrates a comparison between the used network and a proposed hexagonal network.

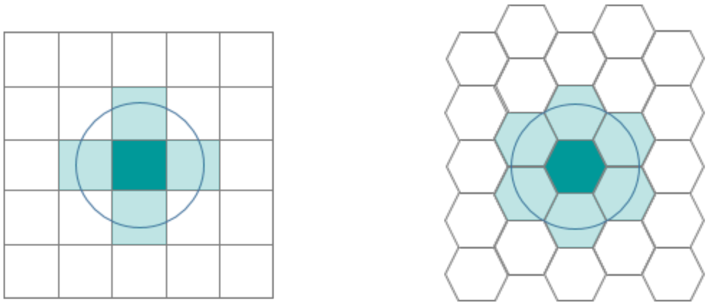


Figure 108. The regular square network model used in this thesis, left, and hexagonal network, right, with a more accurate representation of distance in at directions of 45 degrees. Both with distance band and zonal coverage.

The benefit between the two network datasets is apparent with a larger zone of coverage with the same distance band. Further the ability to move in the diagonal space increases cost path accuracy [179]. However, at the resolution considered in this work with a 2km cell size, the computational time was deemed to be too limiting. Understanding the benefits of the hexagonal system and the computational drawback a prosed combined network could be designed,

A further improvement to the cost path analysis is the network dataset analysis tools themselves. Within the allocation model the ability to increase the cost of sections of the network layer or to exclude regions entirely could increase the accuracy of allocation results. Sites in complicated seabed geotechnical regions could be classed as more 'expensive' to operate through.

10.1.4 Array Electrical Configuration

Within the first allocation modelling system to reduce the 2km cells locations to combined grouped array clusters only one electrical configuration was assumed. A similar spatial allocation process was explored in the work of [126] who explored the roll of electrical configurations in reducing cost for 2030 North Sea offshore wind developments. Using multiple cables to connect arrays to the grid could be considered costly. Although within this work arrays ranged between 100MW and 800MW. Grouping clusters with combined export cables could be modelled for its impact on costs.

10.1.5 Port Analysis

Port analysis was based upon the established assumptions for capacity from relevant literature. However, there are certain assumptions that could be expanded on, including but not limited to, weather window analysis, travel time, port turnaround time, port competition and motherships.

The idea of using large scale mother ships to cut costs has been examined in the past by the wind industry with several designs underway. The work of [180] highlighted the cost benefit of mother ship craft to wind projects. The return of expenditure over project lifetimes was assessed and it was found to be justified over the winter months when traditional operations are reduced. However, it is known that over the winter months that offshore wind farms not only produce greater levels of power but also are more expose.

Port competition is the idea that the floating technology will not be the only facility user. One key competitor that will require the same facilities is the fixed wind industry. Spatial competition for ports could be established through the application of the known planned fixed offshore wind installations and the associated ports. Those ports would therefore already have a number of turbines to roll out in the project span and would be restricted.

10.1.6 Power Flow Anlysis

It was identified that a large degree of similarity in data was found between the allocation modelling and what is known as optimal power flow analysis. Initially an approach had been considered to incorporate the data into a wider GIS power flow model. However, due to complexities in combing the two systems this approach was not explored in this work in details. However, an approach could be explored through the application of several transmission modelling techniques in optimisation software.

When a transmission network is analysed by calculating the optimal distribution of products, the mathematical process is known as OPF (Optimal Power Flow). The term DC (OPF) is taken as the linearized approximation for an AC OPF and not a DC power line representation. Links between nodes represent bidirectional flow and the nodal junction network system applies Kirchhoffs law, Figure 109, within OPF theory which applies to all nodes within the system.

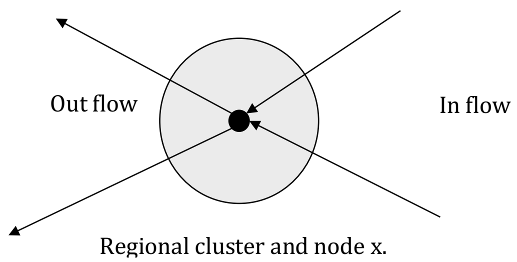


Figure 109. Kirchhoff's circuit law principle. Sum of power generated at regional node x, and the total inflow into node x must equal the demand at x.

10.1.7 Combination of Tools

A further and considerable development in this field could be found from the unification of the methods and tools used in this work. By using a unified modelling approach, the assessments could be made more streamlined. Python could be used in this way to create a series of assessment tool kits with graphical user interfaces (GUI) for users with limited modelling experience. Each of the research topics, associated datasets, methods and outputs could be hosted in QGIS. While an interface between QGIS and python or, as used in this work, Excel would be required for the grid analysis and genetic algorithm work.

10.2 Application

The tools utilised in this work have been applied to a number of scenarios to demonstrate the relationships between infrastructure and potential floating renewable deployments. Aside from the expanded methods that could be considered for further work there are a number of further applications that could be examined.

10.2.1 Technology

In order to simplify the modelling process and focus this work on the relationships between topics, two technologies have been explored. There are however a variety of technologies within the floating wave and wind field. The tools established in this work could be used to highlight the relative merits and roadblocks to a variety of technology types. Most notably are the more advanced floating wind technologies, including but not limited to, the Windfloat concept. Windfloat is a semisubmersible that has seen pilot stage success [18] and plans are ongoing at a number of sites to utilise this technology type to array scale. This technology has a distinct advantage over the Hywind spare buoy device assessed in this work which can only use ports with local depths greater than 70m due to its shallow draught.

10.2.2 Energy Targets

While the work in this PhD focussed on a 2030 32% target set out by the European Union more varied targets could be set in the model. Energy market modelling could be made to incorporate future targets of greater than 32%. Furthermore, the modelling could be extended out to incorporate more data looking forwards to 2050 and increasing levels of renewable penetration. The impact of increasing the penetration level of renewables could yield greater use of the floating resource. The genetic algorithm solver could be configured to simulate of for a range of min-max of 32-50% renewable penetration.

10.2.3 Scenarios

This work considered a number of scenarios that involved the energy partnership between nationals and the combination of the EEZ and electrical grid, by expanding the development area and demand pool greater numbers of sites can be utilised. One type of scenario that was not considered in this work was to assess the impact on political disputes on the power sector. Brexit, the colloquialised term for the United Kingdom's exit from the European Union in 2021 was one such example. Models could be simulated to highlight the impact of having to arrange new agreements on interconnection and power supply.

Another scenario type that could be addressed is the development of new grid and port capacities. By evaluating the impact on the utilisation of available sites by current infrastructure the locations of new ports and transmission lines could be modelled, and their impact assessed.

One such system that has gained favour at the time of writing is the North Sea Wind Power Hub. The project involves the cooperation of the UK, Netherlands, Denmark and Germany and the development of an energy island on Dogger bank, a shallow sand bank in the centre of the North Sea. It could involve the development of an artificial island and multiple interconnections to each nation. The models developed in this work could be used to show the relative sensitivities of each component and the subsequent need for focused assessments going forwards. Furthermore, a similar assessment could be made for locations around the Scilly isles with connections to the UK France and Ireland as well as multiple other locations that could yield high volumes of suitable sites with multiple national stakeholders.

10.2.4 Global Application

Western Europe was selected in this work due to the sectors maturity and favourable resource potential for floating wave and wind. However, the modelling tools developed could be applied to any geography, if similar datasets could be sourced. Floating technologies have been explored at length off the coast west coast of the US and by the Japanese, Taiwanese and South Korean governments. All four countries have been looking to exploit a floating wind resource with a number of pilot projects and developer of the Hywind project, Equinor highlighting these regions as development hotspots [177].

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12. APPENDICES

12.1 APPENDIX I. Analytical Overview

12.1.1 Data Sources Tables

Chapter	Data	Source
2	Marine regions	IHO (IHO, no date)
3	Submerged landscapes	EMODnet (Cogea srl, 2015a)
3	Bathymetry	EMODnet (Cogea srl, 2015a)
4	Wave and Wind Resource Dataset	University of Athens (C. Kalogeri, 2018)
5	Sub Marine Cables	EMODnet (Cogea srl, 2015a)
5	Oil and Gas Installations	EMODnet (Cogea srl, 2015b)
5	Fixed Wind Farms in Operation or Development	EMODnet (Centro Tecnologico del Mar - Fundación CETMAR, 2016)
5	Marine Archelogy	EMODnet (MACHU project, 2016)
5	Shipping Density	ESA (ESA - CLS, 2009)
5	Vessel Tracks	MMO (UK GOV - MMO, 2014)
5	Natura 2000	European Environment Agency, 2019
5	Human Activities, Aggregates	EMODnet (AZTI-Technalia, 2018)
5	Offshore Installations	EMODnet (Cogea srl, 2015b)
5	Blue Hub: Fishing actives	European Commission, 2017
7	TYDP-2030	ENTSOE, 2018
7	NUTS Polygon	Eurostat 2019
7	Power Statistics	ENTSOE, 2019
7	Pypsa Eur- EU grid Model	Github (H. Jonas, 2018)
7	SciGrid-EU transmission data	SciGRID, 2017
7	European Solar Radiation Data	European Commission, 2017
7	European Monthly wind speed (MAPPE model)	European Commission JRC, 2015
7	World Port Index	WPI, 2018
7	European Transmission Atlas	ENTSOE, 2019

12.2 APPENDIX II. Resource

12.2.1 Resource Bins Identification

Establishing the regions to which resource bins could be applied is important due to the nature of location based met ocean characteristics. Bathymetry, distance to shore and exposure of sites to climatic conditions that drive resource, such as fetch, all have a role in estimating the bin size and location. The resource variables chosen for the assessment are the annual mean wind speed and wave power directly extracted from the resource dataset, as pictured below.

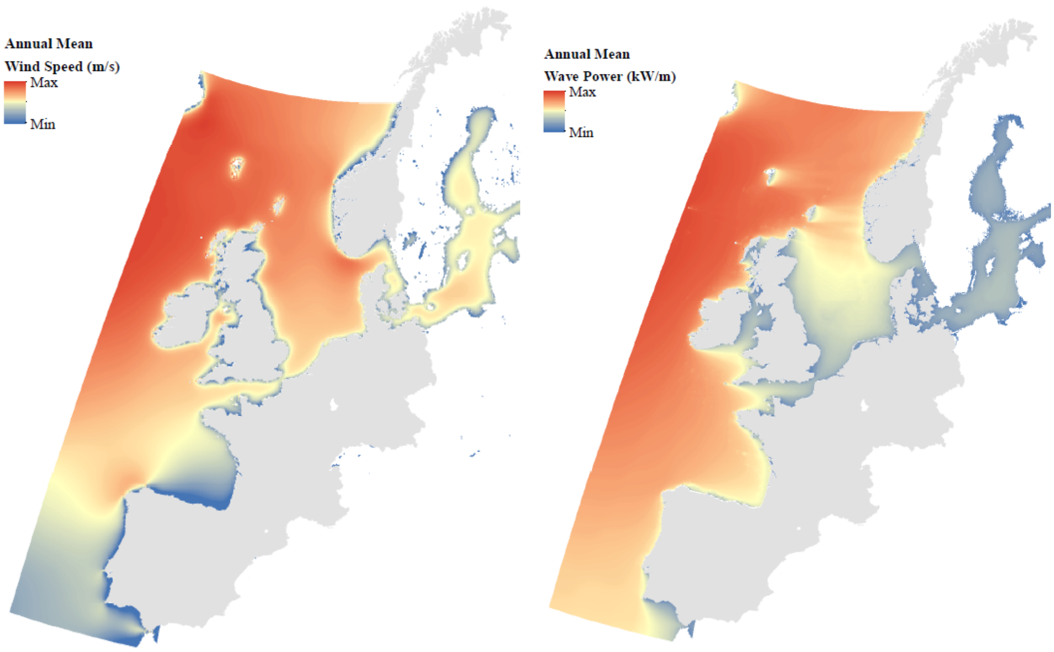

Figure 110. Offshore wind (left) and wave (right) mean annual resource.

The total number of points in the research area where found to be 201400 data points which is well beyond the computational capability or necessity for this work. At deeper water, farther from shore with unimpeded fetch distances, points can be assumed to be more similar in resource magnitude. Therefore, the goal of the reduction process is to maintain extremes in magnitude and represent change while removing unnecessary points. To do so the ARC GIS tool kit in the bespoke Maritime Bathymetry extension was applied. The tool reduces point density typical is applied to bathymetric data. However, in this case selections were iterated for both resource types to reduce the point count to approximately 50 locations. To avoid nearshore meteorological and wave climate complications a minimum distance from shore was set as 50km and a minimum and maximum depth range of 30 - 1000 m, based on technology limitations. The algorithm therefore only considers resource magnitudes or z values within this range. The process is similar to the raster to multi point process which also thins data sets based on the Raster to Multipoint z thinning algorithm in ARC GIS. Except for the magnitude bias and proximity neighbour settings which can be applied to conditional assessments required in this work. The algorithm was applied to establish a relationship of high resource, z, and values relative to neighbouring features up to 50km away. The result of which is a representation of the locally significant high resource. A comparison between the two thinning processes can be observed in following figures for wind speed.

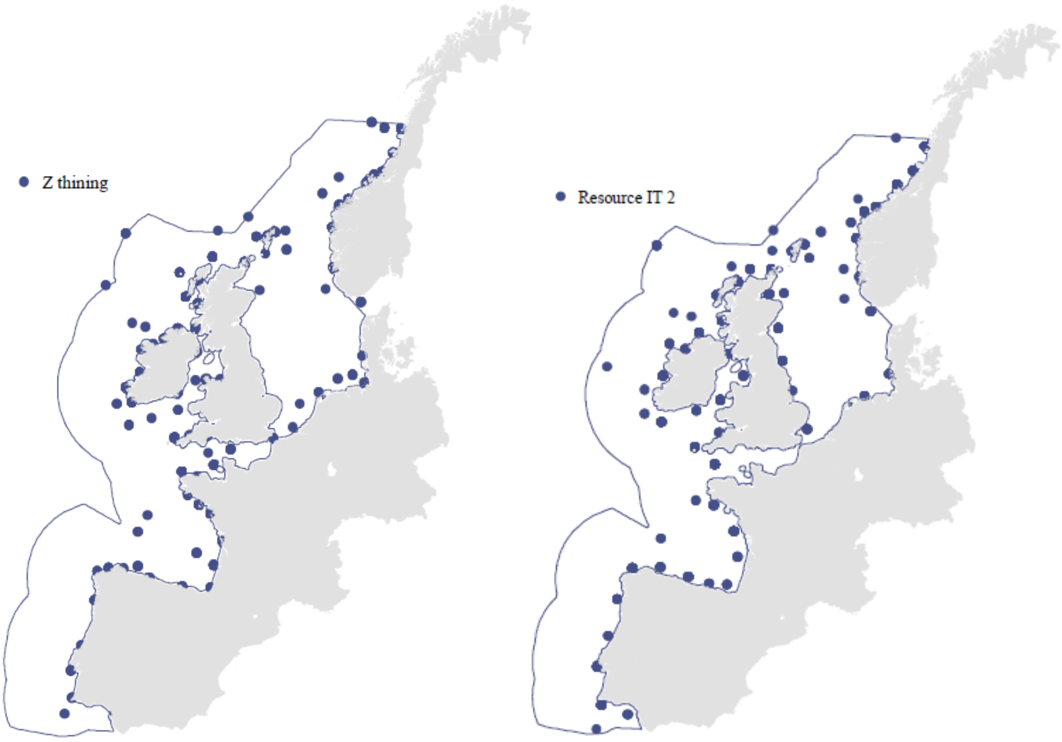

Figure 111. Example result of Z thinning (left) to approximately 65 points. Location bias Point Reduction (right).

The significance of the radial thinning processes observed where the majority of points moves away from coastlines to offshore locations. Representing the two resource criteria of wind speed and wave power was established in the same process. Considerable resource overlap is present, which can be observed when comparing the two maps. An amalgamation of both data sets is observed in Figure 112 where the final bins selection is presented.

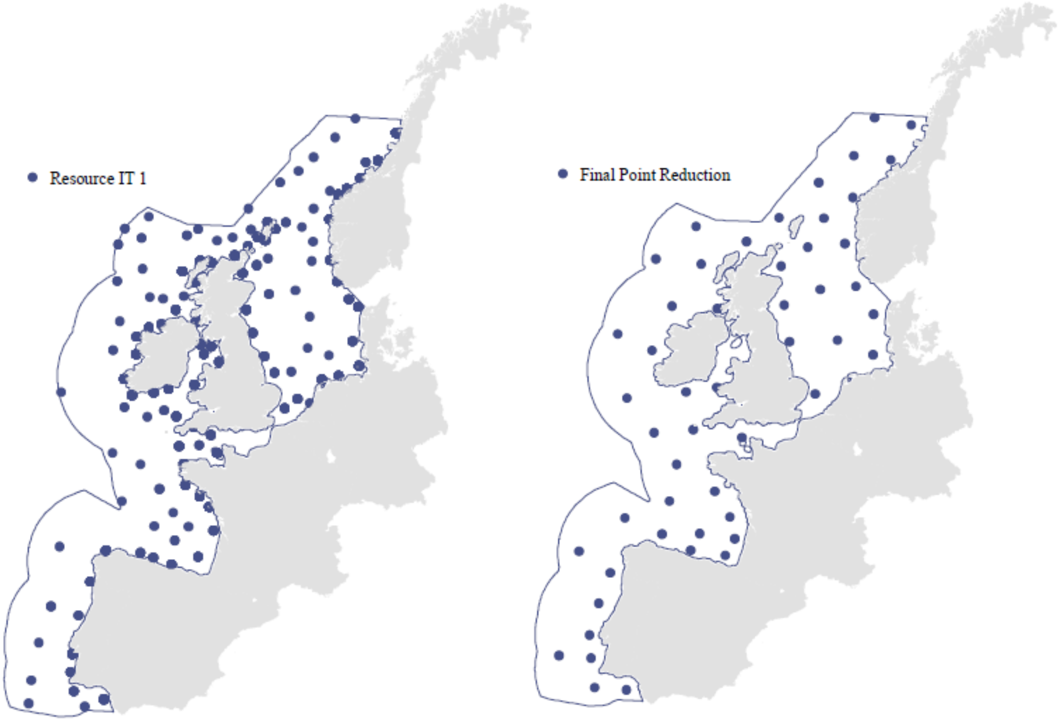

Figure 112. Combined wave and wind resource locations (left), Overlap removal final resource bin (right) point reduction to 51 locations.

The resource point locations represent the spatial significance of resources located within the distance boundary.

12.2.2 Resource Directionality

Directionality output of resource data points over the 10 year hindcast model.

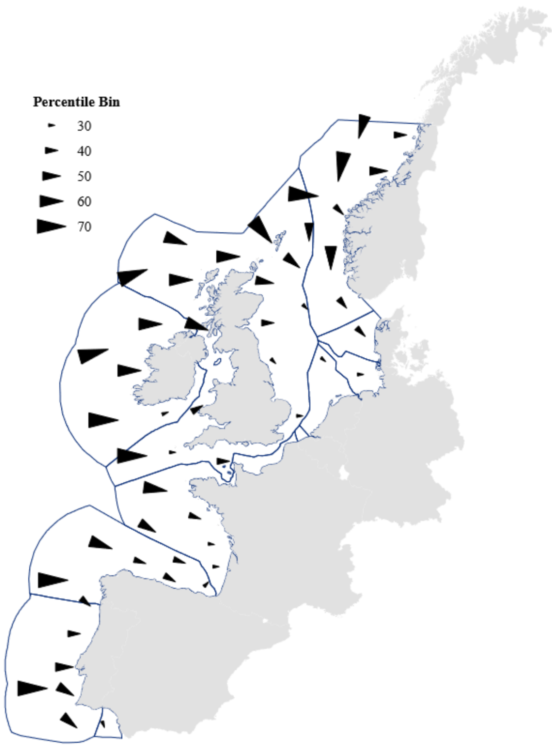

Figure 113. Annual mean wave (top) wind (bottom) direction and bin percentage.

12.3 APPENDIX II. Mooring Suitability

12.3.1 Bathymetry

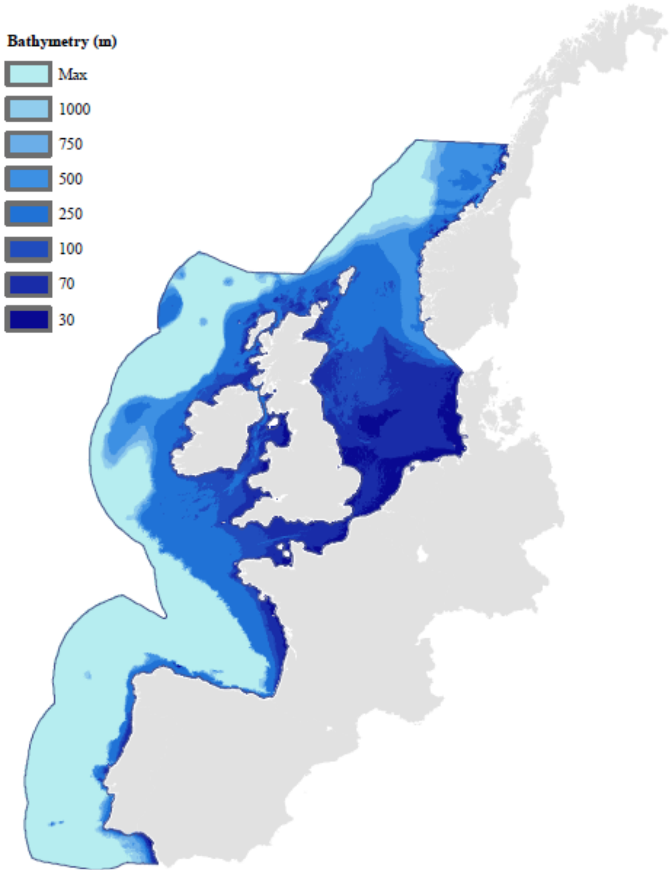

Figure 114. Bathymetry over study area

12.4 APPENDIX III. Marine Policy

12.4.1 Industry Spatial Representation

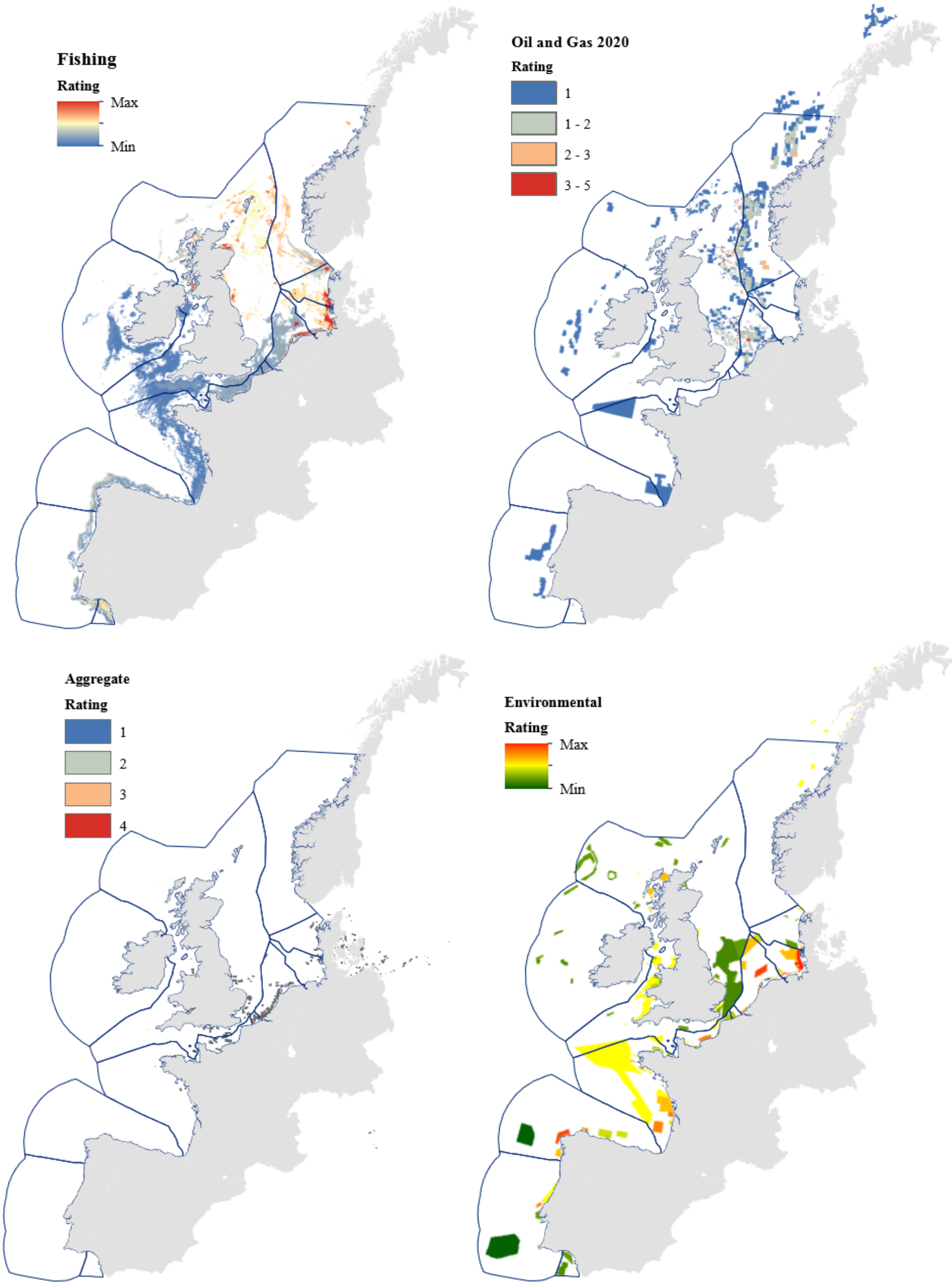

Figure 115. Marine policy data layer inputs

12.4.2 Industry Weighting

Where a value closer to 0.33 represents a natural stance and closer to 0 the most sensitive.

Table 44. National preference weightings of marine industries considered

ID	Fisheries	Aggregates	Hydrocarbon	WWE
BE	0.28	0.21	0.33	0.17
DE	0.29	0.24	0.33	0.14
DK	0.29	0.28	0.26	0.17
ES	0.22	0.28	0.33	0.17
FR	0.26	0.28	0.33	0.14
IE	0.24	0.29	0.33	0.15
NL	0.27	0.24	0.26	0.23
NO	0.30	0.32	0.17	0.21
PT	0.25	0.29	0.33	0.13
UK	0.31	0.27	0.22	0.21

12.5 APPENDIX IV. Location Allocation

12.5.1 Offshore network

The infrastructure modelling utilises a regular spaced grid through which allocation modelling takes place.

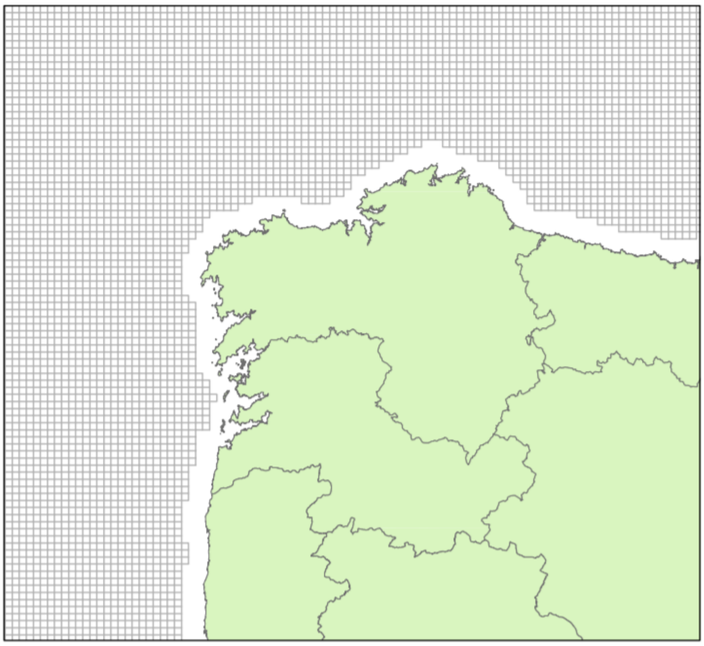

Figure 116 – Extract example of network for cost path matrix analysis

12.6 APPENDIXVI. Port Suitability

12.6.1 Update Table

Table 45. Assumed known port upgrades

Location		Upgrade Period				
PORT_NAME	COUNTRY	2018	2020	2025	2030	SOURCE
ZEEBRUGGE	BE					
OOSTENDE	BE					
BREMERHAVEN	DE					
WILHELMSHAVEN	DE					
EMDEN	DE					
CUXHAVEN	DE					
ESBJERG	DK				1	[181]
CADIZ	ES					
FERROL	ES					
PUERTO DE BILBAO	ES					
VIGO	ES					
SANTANDER	ES					
MARIN	ES					
GIJON	ES					
PUERTO DE PASAJES	ES					
AVILES	ES					
PORT OF LE HAVRE	FR					
DUNKERQUE PORT EST	FR					
RADE DE BREST	FR		1			[182]
ST NAZAIRE	FR					
RADE DE CHERBOURG	FR					
DUNKERQUE PORT OUEST	FR					
CALAIS	FR					
LA PALLICE	FR					
BOULOGNE-SUR-MER	FR					
LE VERDON	FR					
BELFAST	GB					
SOUTHAMPTON	GB					
TEESPORT	GB					
PORTSMOUTH HARBOUR	GB					
CROMARTY	GB					
SWANSEA	GB					
ROSYTH	GB					
KINGSTON UPON HULL	GB					
CARDIFF	GB					
LIVERPOOL	GB					
TYNEMOUTH	GB					
BARROW IN FURNESS	GB					
INVERGORDON	GB					
METHIL	GB					
MOSTYN	GB					
IMMINGHAM	GB			1		[183]

HARWICH	GB		
BARRY	GB		
GRIMSBY	GB		
AVONMOUTH	GB		
DUBLIN	IE		
COBH	IE	1	[184]
ROTTERDAM	NL		
EEMSHAVEN	NL		
VLISSINGEN	NL		
DEN HELDER	NL		
IJMUIDEN	NL		
STAVANGER	NO		
TRANNESET	NO		
THAMSHAMM	NO		
MONGSTAD	NO		
BERGEN	NO		
NAMSOS	NO		
MO INLET	NO		
ALESUND	NO		
AVEIRO	PT		
LISBOA	PT		
VIANA DO CASTELO	PT		
SETUBAL	PT		
KISHORN	UK	1	[185]

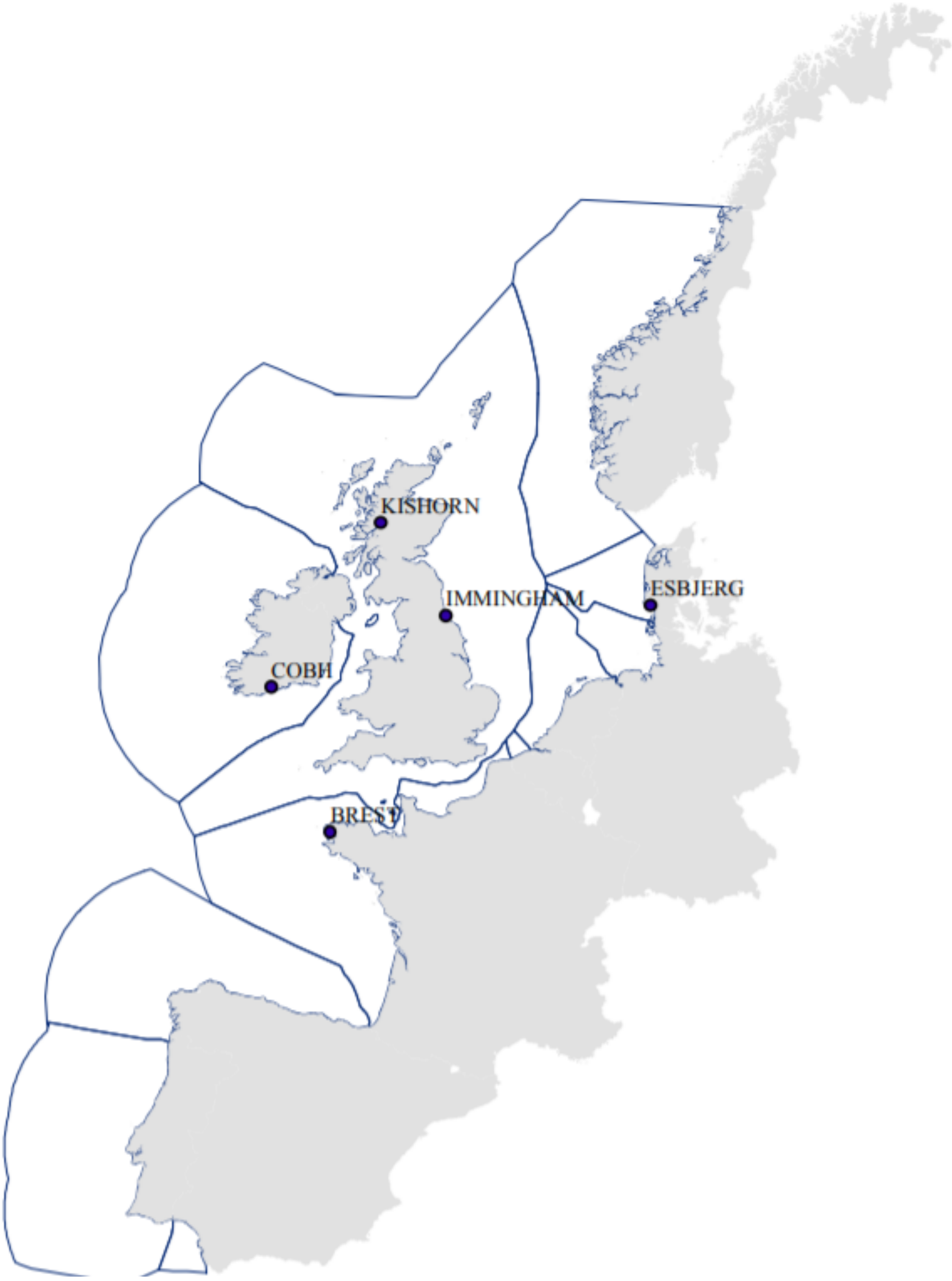

Figure 117. Assumed known port upgrades map

12.7 APPENDIXVI. Grid Assessment Model

12.7.1 Test Case

Table 46. Iberian Test Case 2030

	WWE	RES	DISP	WWE	RES	DISP	RTC	DEM
NODE	C_g	C_g	C_g	MW	MW	MW	MW	MW
ESP 1	Cm	70	80	500	600	700	4400	6400
ESP 10	0	70	100	0	1300	1400	10500	15400
ESP 11	0	70	100	0	1000	1200	7100	10500
ESP 12	0	70	110	0	900	4200	6000	8900
ESP 13	0	70	100	0	2400	3900	13400	19700
ESP 14	0	70	100	0	9000	2100	21700	31900
ESP 15	0	70	100	0	1800	4800	6200	9200
ESP 2	0	70	80	0	100	3000	4900	7200
ESP 3	0	70	100	0	800	2100	8200	12100
ESP 4	80	70	80	500	3000	400	4000	5900
ESP 5	0	70	120	0	3200	2900	9000	13200
ESP 6	80	70	0	500	2700	0	7100	10400
ESP 7	0	70	70	0	2000	2600	7500	11100
ESP 8	0	70	80	0	900	2000	11200	16400
ESP 9	0	70	70	0	300	2500	1700	2600
PRT 1	0	70	0	0	400	0	5200	7600
PRT 2	0	70	70	0	1500	1200	8900	13000
PRT 3	0	70	0	0	700	0	6400	9400
PRT 4	0	70	0	0	4400	0	3500	5100
PRT 5	0	70	100	0	200	300	4600	6700
PRT 6	80	70	110	500	1400	800	5300	7700
PRT 7	0	70	0	0	700	0	2200	3200
PRT 8	0	70	100	0	900	1600	6600	9600

12.8 APPENDIXVII. Results

12.8.1 Cost Reduction Spatial Results

To demonstrate the roll of cost reductions over time as well as the impact infrastructure has on LCOE a second all study area scenario was performed. A technology improvement rate was factored in over the time steps. The results represent the total volume of allocated roll out across the study area with the improvements in infrastructure and the assumed reduction in LCOE. The results for each time frame are presented below for wind where infrastructure capability constrained LCOE is compared with the unconstrained LCOE.

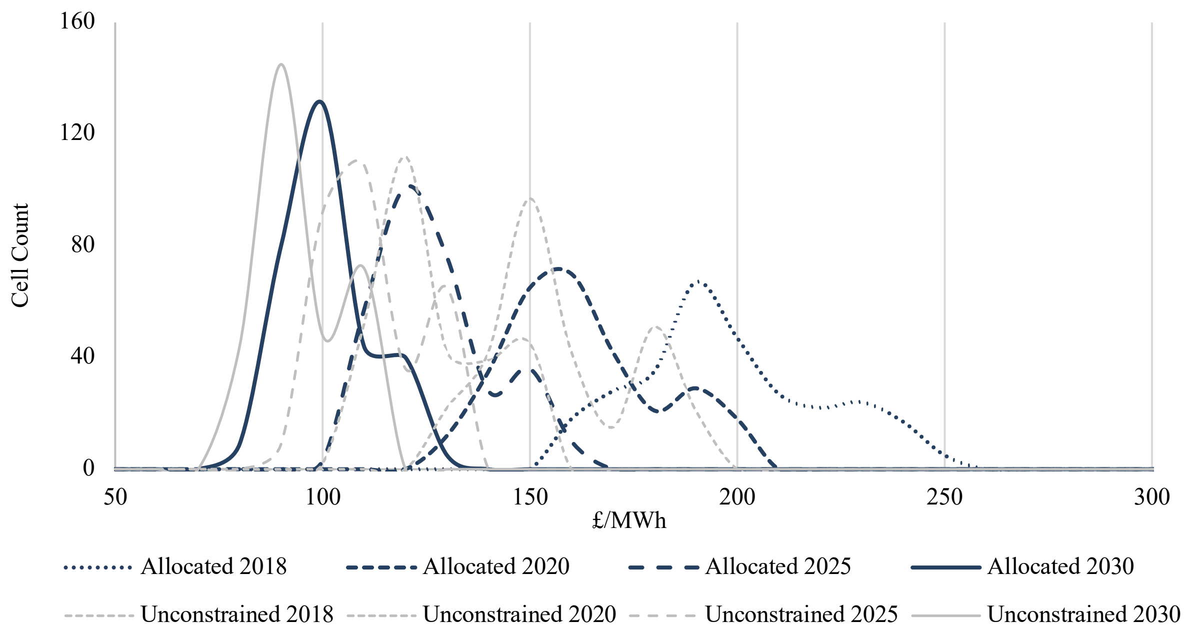

Figure 118. Study area wind LCOE curves of the distributions relative to the potential total number of array sites observed in the unconstrained LCOE modelling.

What is observed is a similar cost reduction trend over time between both sets of LCOE results. The influence of capability is also represented for wind as the difference between unconstrained and allocated LCOE values. The mean variation across all the forecasts was found to be approximately 8% due to infrastructure allocation constrains. The following figure demonstrates the same set results for the wave technology roll out forecasts.

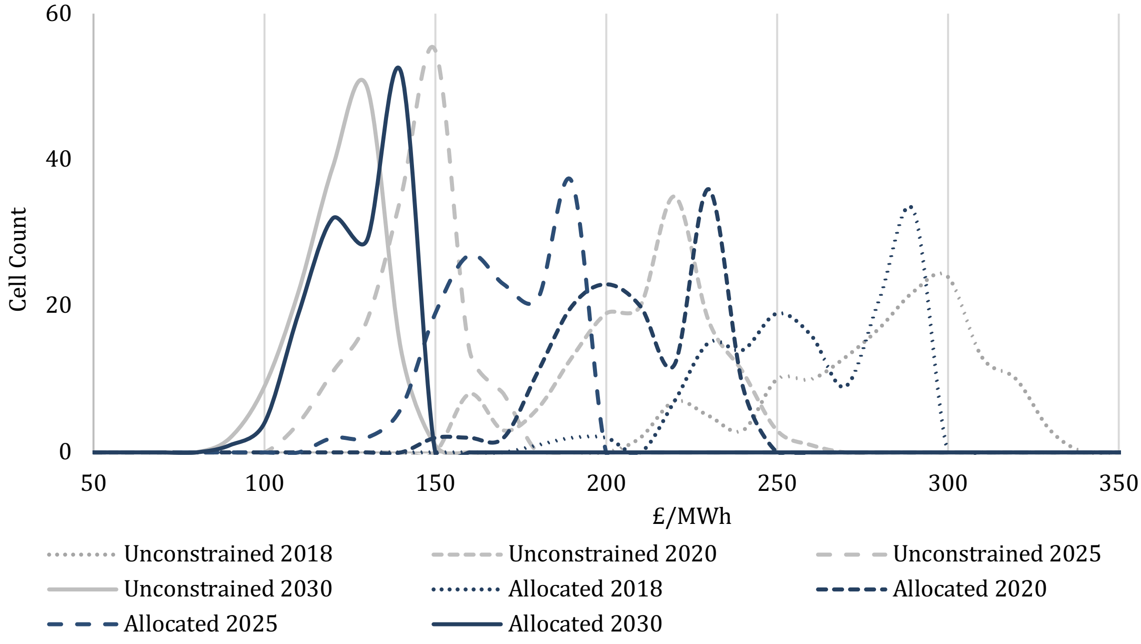

Figure 119. Study area wave LCOE curves of the distributions relative to the potential total number of array sites observed in the unconstrained LCOE modelling.

A similar trend is observed for the wave technology with regards to reduction over time. While there is variability in cost reduction between unconstrained and allocated LCOE a mean approximated change was observed to be 14%. This would indicate that compared to the wind potential roll out, the LCOE of wave is more effected by infrastructure positioning. The kurtosis observed in the wave plots is significantly wider compared to wind as is the negative skew to the plots and highlights increased variability between LCOE and cell count. However, this does become more focused over time. Initial 2018 and 2020 results are therefore known to be highly spatial dependant in influenced site location relative in infrastructure.

12.8.2 Spatial Distributions of Allocated Infrastructure

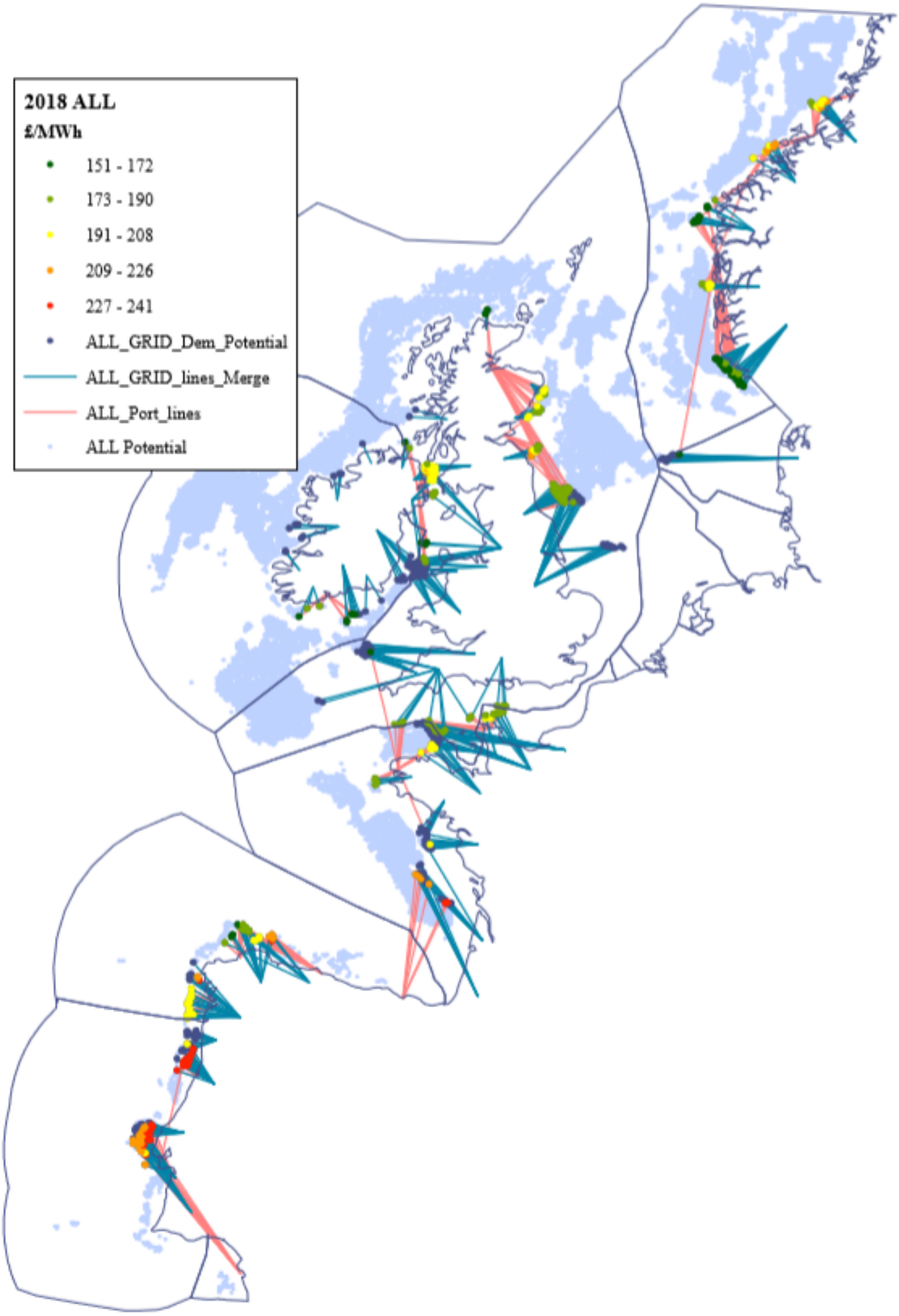

Figure 120. 2018 Wind LCOE distribution with a potential national capacity of, 20GW (UK), 1.5GW (IE), 15GW (NO), DK, 0.1 (GW), 6.6GW (FR), 8.7 (ES), 10 (PT).

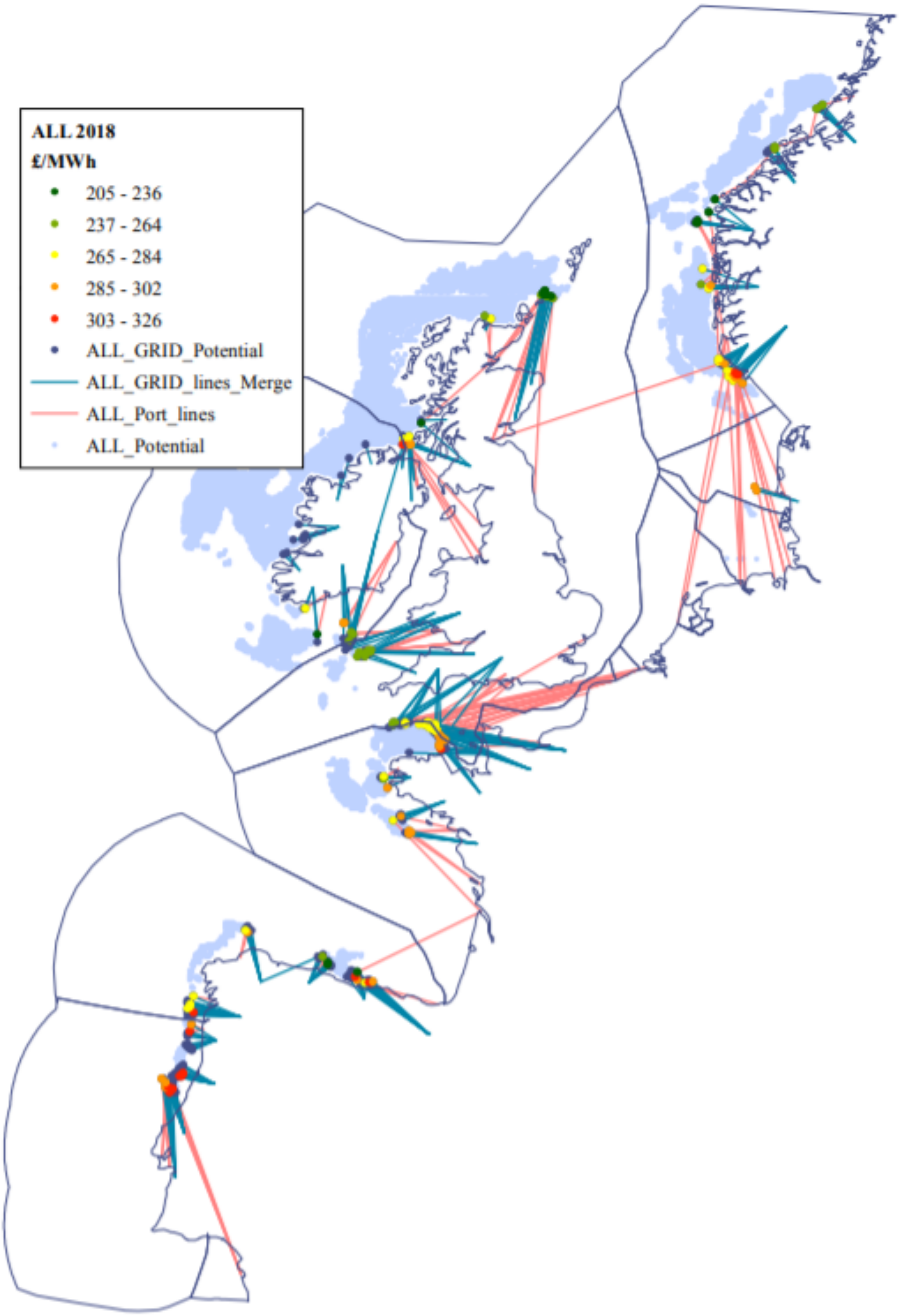

Figure 121. 2018 Wave LCOE distribution with a potential national capacity of, 9.5GW (UK), 1.5GW (IE), 9GW (NO), DK, 0.5 (GW), 6.9GW (FR), 3.3 (ES), 3.8 (PT).

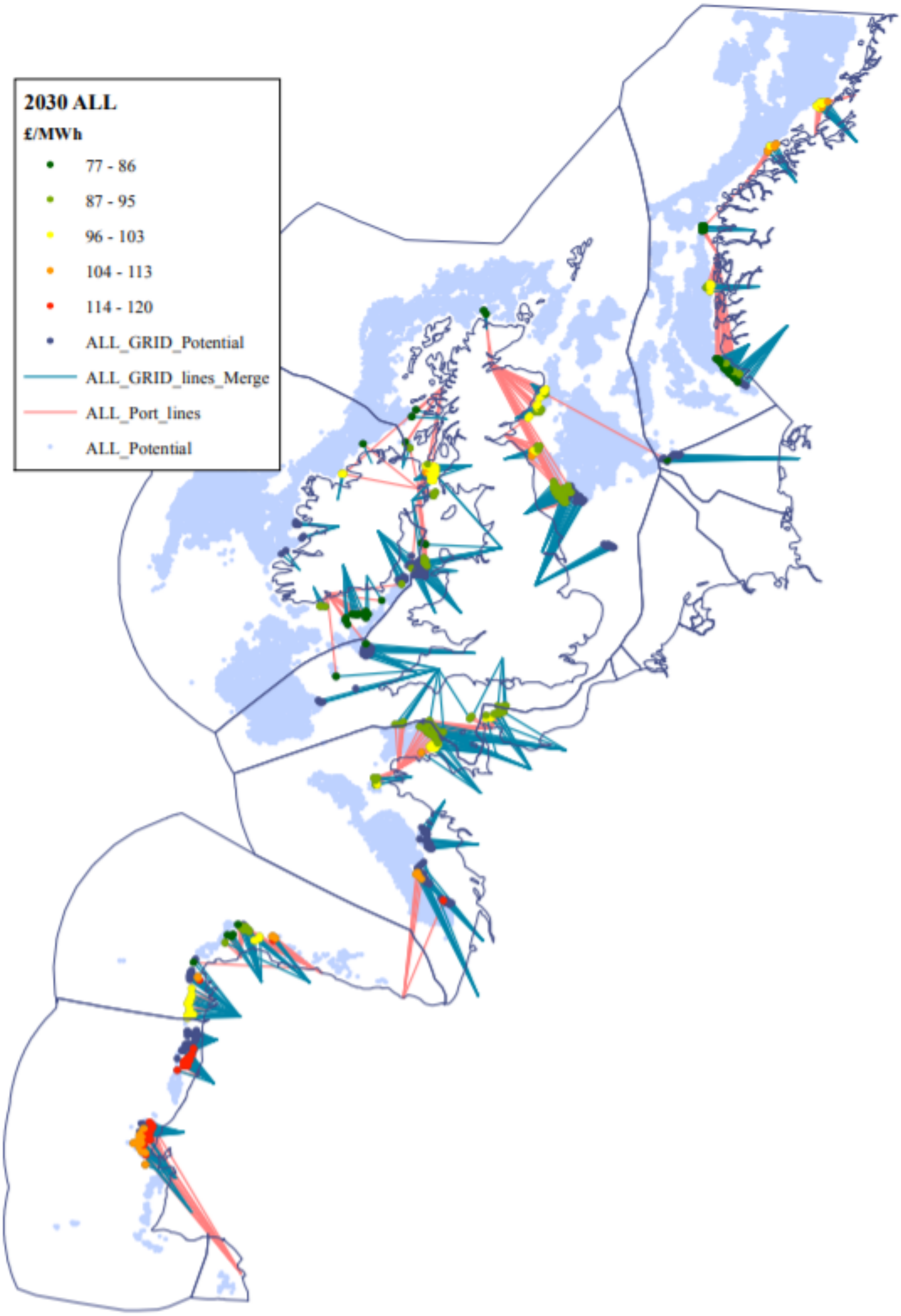

Figure 122. 2030 Wind LCOE distribution with percentage ratio of coverage. With a potential national capacity connection of, 20.5GW (UK), 4.1GW (IE), 15.4GW (NO), DK, 0.2 (GW), 10GW (FR), 8.8GW (ES), 11GW (PT).

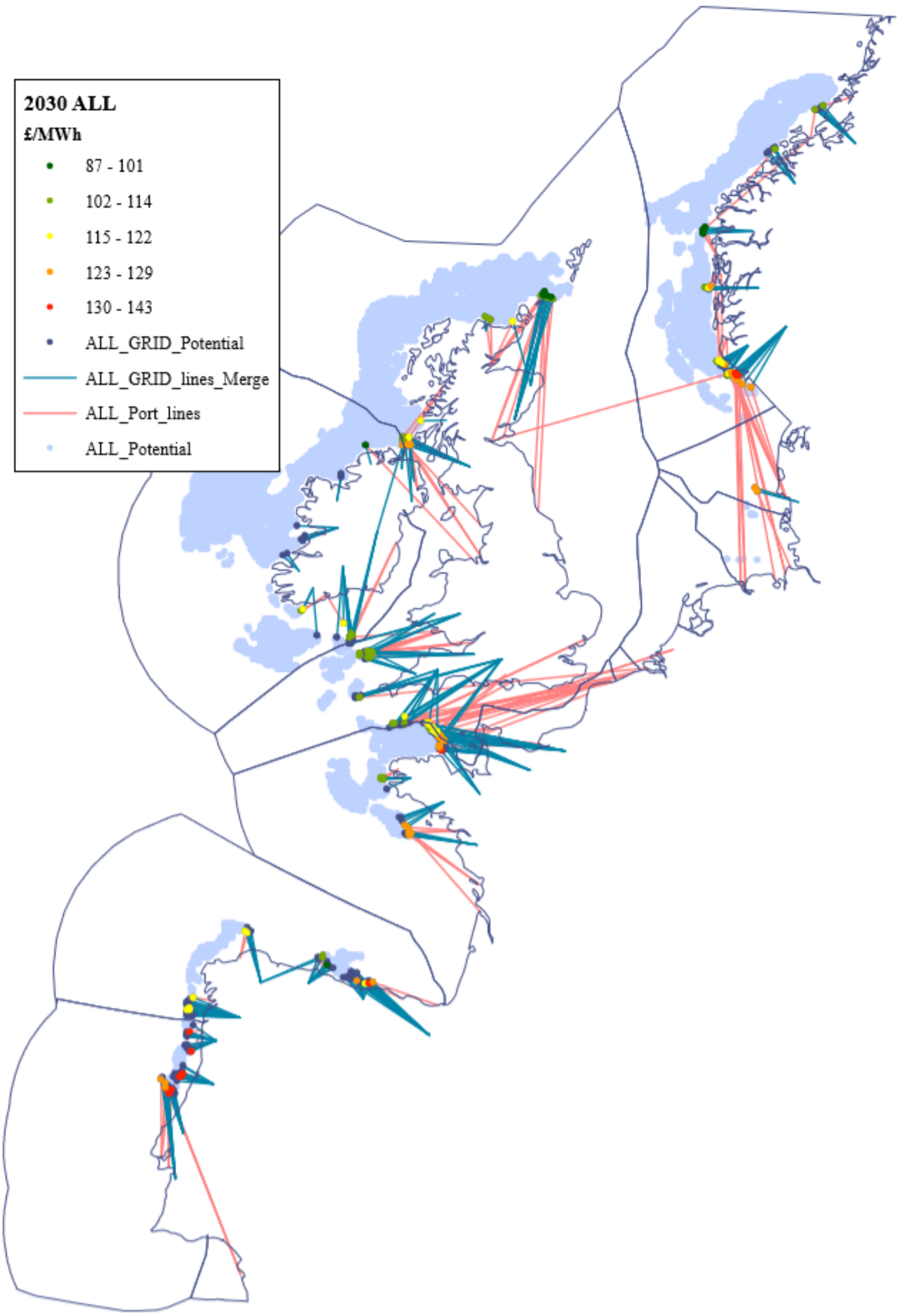

Figure 123. 2030 Wave LCOE distribution with percentage ratio of coverage. With a potential national capacity of, 10GW (UK), 1.8GW (IE), 9.6GW (NO), DK, 0.6 (GW), 8GW (FR), 3.2GW (ES), 3.8GW (PT).

12.8.3 Forecasted simulations for 2020 and 2025

Table 47. Wind Distribution

	2020		2025	
Country	Mean LCOE £MWh	MW Potential	Mean LCOE £MWh	MW Potential
UK	152.4	21000	118.4	21400
IE	144.8	2800	110.1	3900
NO	146.8	15300	114.4	15000
DK	139.3	400	107.7	200
DE	Na	0	Na	0
BE	Na	0	Na	0
NL	Na	0	Na	0
FR	158.4	6700	121.9	10300
ES	158.9	8600	123.6	8600
PT	186.7	10900	145.2	11000
All	155.3	65.7 (GW)	120.2	70.4 (GW)

Table 48. Wave Distribution

	2020		2025	
Country	Mean LCOE £/MWh	MW Potential	Mean LCOE £/MWh	MW Potential
UK	195.0	10600	130.6	9200.0
IE	197.3	1200	144.2	1900.0
NO	200.7	10000	136.0	9600.0
DK	218.7	500	145.4	300.0
DE	Na	0	Na	0.0
BE	Na	0	Na	0.0
NL	Na	0	Na	0.0
FR	214.0	7300	142.4	7700.0
ES	205.6	3300	140.5	3200.0
PT	234.0	3800	155.4	3800.0
All	209.4	36.7 (GW)	142.1	35.7 (GW)

Table 49. 2020 and 2025 coverage ratios for study wide roll out.

	Wind				Wave			
	2020		2025		2020		2025	
Country	% Grid	% Port	% Grid	% Port	% Grid	% Port	% Grid	% Port
UK	5	58	5	59	3	56	3	56
IE	1	32	1	49	1	24	1	31
NO	2	94	2	89	2	69	2	62
DK	100	27	100	18	100	100	100	100
DE	Na	Na	Na	Na	Na	Na	Na	Na
BE	Na	Na	Na	Na	Na	Na	Na	Na
NL	Na	Na	Na	Na	Na	Na	Na	Na
FR	8	32	9	44	5	50	6	52
ES	21	91	23	84	18	26	23	19
PT	28	66	30	62	38	31	32	31
ALL Mean	**24**	**57**	**24**	**58**	**24**	**51**	**24**	**50**